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ABSTRACT

This book is a compilation of a series of papers designed to aid high school teachers in organizing a course in oceanography for high school students. It consists of twelve papers, with references, covering each of the following: (1) Introduction to Oceanography, (2) Geology of the Ocean, (3) The Continental Shelves, (4) Physical Properties of Sea Water, (5) Waves and Tides, (6) Oceanic Circulation, (7) Air-Sea Interaction, (8) Sea Ice, (9) Chemical Oceanography, (10) Marine Biology, (11) The Origin and Development of Life in the Sea, and (12) Aquaculture, Its Status and Potential. The topics suggested are intended to give a balanced coverage to the subject matter of oceanography and provide for a one semester course. It is suggested that the topics be presented with as much laboratory and field work as possible. This work was prepared under an ESEA Title III contract. (HB)

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HIGH SCHOOL OCEANOGRAPHY

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PREFACE

The Oceanographic Education Center has compiled this series of papers to aid teachers in organising a course in oceanography for high school students. The topics included are intended to give a balanced coverage of the subject matter of oceanography and, used in connection with the references, the book contains enough material for a one semester course. Topics have been selected from those listed in An Oceanographic Curriculum for High Schools: Outline, written by R. W. Taber, L. R. LaPorte, and E. C. Smith of the National Oceanographic Data Center and published by the U. S. Naval Oceanographic Office in 1968, and the content of each paper is based on the outline given therein.

In presenting the course to high school students, the teacher should make every attempt to include as much laboratory and field work as possible. Although we know of no high school oceanography laboratory manual, we have found that exercises from courses in biology, physics, chemistry, and earth science can often be adapted to the purpose. An idea of how this can be done might be obtained from reading the exercises contained in An Oceanographic Field Course for the Eighth Grade, which is also published by the Oceanographic Education Center.

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1. INTRODUCTION TO OCEANOGRAPHY

by Susan Hubbard

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> Every advance in our knowledge of the sea makes the interdependence more and more apparent. It is not likely that we shall soon see any general abandonment of this concept of oceanography as a mother science, the branches of which, though necessarily attacked by different disciplines, are intertwined too closely to be torn apart.
>
> Henry B. Bigelow

Definition of Oceanography: Its Early Beginnings

In its broadest sense oceanography is the scientific study of the oceans and of the 71 percent of the earth's surface that lies beneath them. It is composed of several disciplines including physics, chemistry, geology, and biology which, in close cooperation with one another, seek to describe, interpret, and predict the complex processes that occur within the oceans.

Oceanography does not have the characteristics of a universal science as does physics, whose laws are true in all places at all times. Rather, it is more closely allied to the earth sciences, and its law-like generalities apply to a specific body of water at a particular time.

The interconnecting body of water, or World Ocean, that covers so much of the earth has been divided, for convenience' sake, into three, four, or five oceans, depending on the system of names popular at the moment. In addition to these open-ocean areas, which include the Atlantic, Pacific, Indian, Arctic, and Antarctic, oceanography is also concerned with smaller, adjoining bodies of water such as seas, gulfs, bays, straits, fjords, and estuaries.

In the study of this vast amount of water, covering 120 million square miles, biological oceanographers concern themselves with plant and animal life in the sea; geological oceanographers consider the structure and formation of ocean basins and sediments; physical oceanographers study the physical properties of sea water, waves, tides, the distribution and circulation of water masses; and chemical oceanographers study the sea as a solution containing traces of all naturally occurrring elements.

The relationships between these disciplines are not static and their changing patterns reflect the wide variety of problems considered by oceanographers. What combinations of talents tommorrow's problems will encourage are hard to predict, but it seems probable that some form of cooperation will continue as long as the study of the changing sea continues.

Our understanding of the oceans has usually been acquired by a long and costly procedure which begins with a cruise on which a great deal of data are collected. Later this information is processed and analyzed and certain regularities may become apparent, as well as certain notable exceptions. It is interesting to note that the time and effort involved in publishing scientific reports are great in proportion to that expended on the cruise itself. The results from the well-known Challenger Expedition (1872-1876) were not completed until 1895 and studies are still being made on the collections.

As analysis of the data collected at sea proceeds, hypotheses are advanced that try to explain why things exist as they do. Most often the learning process stops here and the tentative hypothesis decided upon stands until another expedition brings back data which suggest an alternate explanation.

Theories concerning coral reefs, for example, have had a particularly colorful, and at times unstable, history. Charles Darwin's theory of subsidence, or of slowly sinking volcanic islands around whose periphery coral reefs grow, was proposed in the mid-1800's and based on observations made by Darwin aboard the surveying ship Beagle. Several decades later, scientists aboard the Challenger, expressed doubt that all the reefs they had observed could be explained by Darwin's theory. Further investigations by the noted American naturalist Alexander Agassiz led him to propound a very different theory which involved the elevation rather than the sinking of island areas.

Opinion see-sawed back and forth between conflicting theories until the 1940's when deep holes drilled into Einiwetok in the Marshall Islands (in conjunction with nuclear weapons tests there) penetrated a coral capping more than 4,000 feet thick before hitting volcanic rock. This upheld Darwin's theory of subsiding volcanic islands which, after 100 years, is back in vogue.

Dr. Henry Stommel, a physical oceanographer known for his work on the Gulf Stream, has pointed out that this process involving observvation, analysis and the postulation of theories too rarely completes the cycle by including an experiment, such as the Einiwetok drilling, designed to prove or disprove the hypothesis.(7)

In many areas of oceanography, however, such a decisive experiment is difficult to set up, and our understanding of the sea rarely attains the degree of certainty sought after by physicists and chemists.(7)

The ability to test oceanographic theories has been helped, and in some cases made possible, by the advent of computers. The tidal theory, for example, which must take hundreds of variables into account advanced very little in the 50 years following Sir William Thomson's (Lord Kelvin) concept of the tide predictor devised about 1872. Computers, programmed to execute time-consuming mathematical problems, have enabled oceanographers to re-examine and refine this theory and predictions may be made with greater accuracy.

Another approach to the testing of oceanographic theories is to build a model simulating as closely as possible the conditions being studied in the ocean. In the 1890's, for example, Otto Pettersson, a chemist who believed that the main driving force of the North Atlantic currents was the melting of Arctic ice, set up experiments in an aquarium using three tons of ice.(6) At the same time scientists who believed that winds exert a far greater force built models in which currents were simulated with blowers and fans.

Oceanography is usually said to have begun with the sailing of the British ship Challenger in 1872, on a three and a half year expedition around the world. The cruise, undertaken to "investigate all aspects of the deep sea," was a great success and enough information was obtained to outline in a general way the nature of the oceans. Most of the observations were made with such accuracy that the results maintained their usefulness amidst a flood of additional data collected by other nations on cruises patterned after the Challenger Expedition.

Prior to this expedition the depths of the sea - which some thought to be fathomless and others imagined to be quite shallow and monotonously flat - were considered uninhabitable. The depths were pictured as a cold, black zone of absolute stillness and of incredible pressure in which no life of any kind could exist. This belief began to be challenged as sounding lines brought up strange starfish, worms, and other creatures from great depths.

In the 1860's many deep soundings were made between Ireland and Newfoundland to select a suitable route for a submarine telegraph cable.

At the same time that scientists began to suspect that life existed in the deep sea, Darwin's theory of evolution (published in 1859) motivated geologists and zoologists to search for the missing links that would connect fossils to present forms of life for it was believed that a progression of forms could be found, marking the various stages of evolution.

Since the deep sea was then considered to be a changeless environment, it was logical to suppose that creatures living there had not changed much through the ages. One of the main reasons for sponsoring the Challenger Expedition was to find this hypothetical community of living fossils. In this effort the scientists were disappointed although the expedition is credited with the discovery of close to 4,000 new species.

In this country the motivation for early studies of the sea came more practical considerations of navigation than from the intriguing questions posed by natural history. Matthew Fontaine Maury, superintendent of the Navy's Depot of Charts and Instruments, instituted a plan in 1842 whereby he received information on winds and currents from ship captains in return for copies of the Wind and Current Charts of the North Atlantic published by the Depot. In this way Maury collected a vast amount of information and in 1855 published the first English language text on oceanography titled The Physical Geography of the Sea.

Phases in Oceanography

Less than 100 years have passed since oceanography became a recognizable field, yet in this short time it has passed through at least three phases to emerge as the high-powered, high priced example of "big science" that we speak of today as oceanography or oceanology.

Using a prominent physical oceanographer's terminology, oceanography opened with an "Era of Exploration" which began with the voyage of the Challenger and extended until the beginning of World War I in 1914. Oceanographic expeditions during this period were characterized by long, independent cruises during which observations were made at widely-spaced stations or stops along a route that circled an ocean or even the world.

The ability to collect accurate data at this time depended largely upon the design of the instruments being used. When the Challenger put to sea the soundings for charting the depths of the oceans were made by lowering weights on the end of a thick hemp line. Especially in waters several miles deep, this procedure took a great deal of time and was susceptible to several sources of error.

The Challenger was equipped with a new sounding machine, designed by Lord Kelvin, that used piano wire instead of hemp, but the reel collapsed on the first trial and it was not used again during the expedition. A successful model was installed and used aboard the U. S. cable ship Tuscarora in 1873. The use of wire was extended to trawling and dredging operations a few years later aboard the Coast Survey Steamer Blake.

Prince Albert I of Monaco was an early oceanographer whose contributions included new methods and equipment as well as the collection of data and the establishment of a museum, labs, and a teaching facility in Paris and Monaco.

The prince built several pelagic or mid-water trawls for the collection of fish and other swimming organisms. He also added to his collections - especially of cuttlefish - by shooting whales and examining the contents of their stomachs for, as was then stated, "the whale is still far more capable of catching living marine creatures than any scientific appliance hitherto invented."(4)

In spite of considerable efforts the oceans were very thinly covered, scientifically, by the end of the 19th century. Entire submarine mountain ranges existed undiscovered, for along the few cruise-tracks that crossed them, soundings might only have been made every several hundred miles. Only in the 1920's when radio acoustic position finding and automatic echo-sounding became available could knowledge of the deep-sea topography advance from the general to the particular.

This early era did, however, provide the information needed to formulate a general idea of the ocean basins, the water masses that circulate within them, and the plants and animals that live at every depth.

At the turn of the century a group of Scandinavian oceanographers especially interested in extending the theories of physics to the phenomena of the sea developed a new approach to ocean studies. Instead of a single large vessel putting out to sea for several years they began to use smaller ships for numerous cruises, several of which might retrace the same cruise track but at different seasons of the year. Stations were spaced quite close together and a degree of detail was acquired not possible with larger expeditions.

In 1890, for example, Otto Petterson studied the seas west of Sweden with five vessels in order to obtain a clearer understanding of the distribution of water masses and currents. It had been found earlier that economically important schools of herring favored a particular water mass, that is they tended to stay within a large volume of water of particular temperature and salinity. The accurate predictions of the seasonal movements of this water mass would be of obvious benefit to fishermen.(6)

This type of more or less continuous investigation of a body of water, known as the systematic approach, developed as the study of the oceans progressed from a predominantly descriptive approach - whereby general characteristics are described from data gathered on independent cruises - to a dynamic approach - whereby the oceans are regarded as continuously changing and measurements must be repeated to reflect the changes.

Also indicative of the changing approach in oceanography was the establishment of several international organizations for the co-operative study of the sea. Best known among these is the International Council for the Exploration of the Seas (ICES) organized in 1902. Its primary purpose was the collection of data pertinent to fisheries' research, but in view of the close inter-relationships among the disciplines in oceanography it was inevitable that the council's work would advance the sciences of the seas in many areas. This interdependence was expressed in the proposals presented at the first ICES meeting. It was, at that time, suggested that

> Periodic and simultaneous scientific observations [be made] four times a year, on the salinity of sea water, it temperature, its content of different gases, the quality and quantity of the plankton . . . [and upon] the system of currents, because upon them depends the variation of the plankton, the food of fishes . . . and also the appearance and disappearance of migrant fishes, and upon temperature of the sea on which depends the climate and the weather in the countries bordering on the North Sea.

Systematic investigations proved to be an effective way of studying smaller seas and by the 1920's many nations began using this approach to study larger areas of the World Ocean as well.

The second period in oceanography, which Georg Wüst calls the "Era of National Systematic and Dynamic Ocean Surveys," extended appromimately from the time of the well known German Atlantic Expedition aboard the Meteor in 1925 until the beginning of World War II in 1939.

This period was characterized by single research vessels steaming back and forth across an area in order to cover it with a network of stations. The Meteor, for example, crossed the Atlantic 14 times occupying many stations on each transect. At each of these stations subsurface measurements of temperature, oxygen content, salinity and other characteristics were made at regular intervals all the way to the deep-sea bottom. The cruise is also credited with being the first to systematically employ an echo-sounder although at that time the range of the instrument was limited.

The example set by the Meteor was followed by many other countries. From 1932 to 1934 the British ship Discovery II systematically studied the Antarctic Ocean while after 1931 the newly acquired Atlantis, belonging to the Woods Hole Oceanographic Institution, undertook detailed studies in the western North Atlantic.

Many cruises were suspended during World War II although the war did a great deal in other ways to push oceanography from a loosely organized "general science of the seas" to a more cohesive assault on the last frontier.

Until the late 1930's the U. S. Navy had been concerned primarily with weather conditions and forecasting as well as with certain surface phenomena such as currents, winds, and waves. During the first years of the war the emphasis shifted towards subsurface measurements as many ways were found to apply oceanographic knowledge to submarine and anti-submarine warfare. Even the noises of the sea made by fish and other organisms were studied, for their snapping and chattering might camouflage sounds emitted by submarines.(5)

Data from the sea surface continued to be important and work was done on wave prediction and coastal surveys, especially as these were related to amphibious landings.

The technology developed during the war introduced many new methods and imporved instruments into the study of the sea, such as precision depth recorders, piston coring apparatus for taking long, unbroken samples of the bottom sediments, and seismic reflection and refraction techniques for obtaining profiles of the structure underlying the sediments. In addition, the range of classical methods of serial measurements - water samplers, reversing thermometers, plankton nets, etc. - was extended to greater depths until even the deepest trenches could be sampled.

These innovations issued in a "Period of New Marine Geological, Geophysical, Biological and Physical Methods," which lasted from 1947 to about 1956. As the name implies, geological and geophysical oceanography assumed places more nearly on a par with the traditional investigations of a physical and biological nature.

Even with improved techniques most data were still collected by single vessels during this period. A significant change took place when the International Geophysical Year, a program for the coordinated study of many aspects of earth sciences including oceanography, got underway in 1957. The study involved ships from many nations and exemplified the character of the most recent phase of oceanography. This, the "Period of Cooperative International Research," has included programs organized for the 23-nation Exploration of the Indian Ocean, the International Cooperative Investigations of the Tropical Atlantic, cooperative fishing studies, and the creation of World Data Centers. Since 1960 many of these activities have been administered by the Intergovernmental Oceanographic Commission, an organization under UNESCO.

Multi-ship studies enable oceanographies to study the sea more nearly as a system rather than as a series of properties artificially separated from each other. These synoptic studies, as they are called, analyze a wide variety of data which are gathered by numerous oceanographers at approximately the same time. Many new relationships between the wind and waves, temperature changes and fish movements, density gradients and current patterns became apparent using this method of investigation.

The eras or periods of oceanography are not rigid divisions. Single research vessels today continue to investigate all parts of the ocean - in fact, in any period investigations are carried out that more closely fit the description of another era.

The progress in oceanography, like that in any science, is a round robin in which new techniques expose new questions to be answered and these in turn require new methods and instruments. It is difficult to predict the directions that future investigations will take, dependent as they are on the scientific and economic questions a generation feels are important, the technological advances that allow certain studies to be made, and a battery of equally elusive unknowns.

One thing, however, is fairly certain. The rate at which oceanography advances in this country will be largely dependent upon the federal government's evaluation of that science's importance to national defense and prosperity. In the President's 1968 report to the Congress on Marine Resources and Engineering Development emphasis was placed on the consideration of a fundamental question: "What portion of the Nation's energy and wealth should be devoted to ocean endeavors, and how?" The future of oceanography will directly reflect the answer that is given.(3)

Present Status of Oceanograpny in the United States

As our knowledge of the seas grows and becomes increasingly accurate more and more information is found to be applicable to specific problems. Oceanography is becoming useful.

Oceanography's first beneficiaries were probably navigators, fishermen in particular. Later, industries were established based on information collected by oceanographers. Plants were started to extract salts and other products from the sea, and oil and gas prospectors depended on oceanographic knowledge of the continental shelf to select drilling sites. By World War II the field was no longer the special province of researchers and professors but had been claimed by businessmen and to a greater extent by government interest. It is in each of these three areas - the realms of universities, the federal government, and private business - that oceanography is advancing today.

Most of the basic, non-mission oriented research in oceanography is carried out in laboratories and on ships affiliated with universities using funds coming in the most part from the federal government.

In 1937 a list of institutions in the United States offering instruction in most aspects of oceanography included five names.(9) The 1969 Oceanology International Yearbook lists 65 (for 1968). These 65 institutions also handled 913 research projects with a total of $33.3 million.(8)

Since the early 1800's the federal government has concerned itself with the fields that were to become part of oceanography. The Coast Survey, forerunner of the Coast and Geodetic Survey, was inaugurated in 1816 and provided the Depot of Charts and Instruments with the information it needed to plot coastal charts. The Depot (now the Naval Oceanographic Office) was established in 1830 to provide America's rapidly growing fleets with aids to navigation.

Since those early beginnings the most rapid advances in oceanography seem to be connected with wars. During World War I the National Research Council was established, and during the second World War both the National Defense Research Council and the Institute of Navigation were organized. These groups saw that the best scientific talent in the country was brought in to advise the government on wartime problems. A great deal of research was accomplished during war years.(5)

At present the Interagency Committee on Oceanography (ICO) co-ordinates the government's oceanographic efforts, spread as they are through at least a dozen different agencies.

The biggest spender in oceanography is the Department of Defense which includes the Navy and its $2 billion-plus budget for submarine and anti-submarine warfare. In addition to this, more than 30 percent of the government's multi-million dollar budget (not including the anti-submarine figure) is spent on defense.(2) The Army Corps of Engineers is also within the Department of Defense and the majority of its funds is spent on the protection of beaches and coastline.

The Department of the Interior, including the Bureaus of Commercial Fisheries and the U. S. Geological Survey, is the second largest spender on oceanography in the government. The Office of Saline Water is also in the department and concerns itself with the problems and possibilities of desalinization projects.

Within the Department of Commerce is the recently formed Environmental Science Services Administration (ESSA). Several branches of the department, including the Coast and Geodetic Survey and the Weather Bureau, will be co-ordinated under ESSA. The new organization has two modern research vessels, the Discoverer and the Oceanographer, which will take part in project SEAMAP, a systematic attempt to chart the sea floor.

Other agencies involved in ocean activities are the Coast Guard, which maintains the Ice Patrol, and the National Science Foundation, which administers grants to many universities, laboratories, and graduate students.

As of 1967, there were at least 1,000 private companies engaged in some aspect of oceanography in this country.(2) Most businesses can be grouped into one of two categories. Either they are divisions of large corporations, or they are small specialized companies. Within both, a further distinction may be made between businesses dealing directly with ocean exploration or exploitation and those acting as the support force for the former by providing them with the vast array of necessary instruments.

Among large corporations now interested in the sea many have worked on aerospace projects and have found it tempting to apply that field's technology to the problems of oceanography.

Within General Dynamics, for example, is the Electric Boat Company, builder of several well-known research submersibles.

Westinghouse in addition to building the diving saucer Deep Star, has also established a new lab for man-in-the-sea and other tests.

Union Carbide is the parent organization for the successful Ocean Systems company, which specializes in providing working divers for a variety of deep jobs. The company has recently begun to operate the research submersible Deep Diver, which allows a pair of divers to leave and re-enter the submarine at depths down to 600 feet.

Included in the category of support industries are hundreds of small instrument and engineering firms, located for the most part along the northeastern and southwestern coasts close to major research facilities.

Not considered in this brief outline are the industries connected with shipping, naval architecture, and commercial fishing.

Conclusion: Preview of Course Material

Oceanography has been briefly described as an observational earth science characterized by a considerable degree of cooperation among its branches. Its early history is connected with the questions posed by natural history and the theory of evolution, practical problems of navigation, cable laying, fishing, and later with theoretical physics.

It has also been noted that research is being carried out by universities, government agencies and private businesses.

In the following weeks basic information concerning the ocean basins, the water masses, ocean circulation, and marine life will be presented. Most of the course material has been taken from disciplines traditionally included in oceanography, such as physics, chemistry, geology, and biology. In addition, the techniques of oceanographic data collection and some applications of this knowledge will be studied.

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2. GEOLOGY OF THE OCEANS

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Introduction

The science of geology is usually defined as the study of the earth, but in fact, until recently, it has been largely limited to the study of the continents. However, many of the rocks exposed on land were once formed beneath the sea, and thus the paradoxical position existed in which geologists knew more about the sea floor as it existed millions of years ago than they did about the present ocean floor. Within the last century our knowledge of the sea floor has rapidly increased, and the concept of marine geology - the study of the present ocean floor - has evolved.

Marine geology is not a unique or isolated science, a knowledge of classical geology is required together with a knowledge of the interdisciplinary concepts of oceanography, The tools the marine geologist uses require a knowledge of physics and mechanical engineering. The distribution of sediments, the composition of the skeletal parts of organisms found in the sediments, the nature of topographic features found on the sea floor, and the interaction of sea and land require an understanding of ocean currents and waves, the chemistry of sea water and the biology and ecology of organisms in the sea. This interdigitation with other sciences makes geology especially attractive as a means of teaching general science as well as earth science.

It should be stressed that this chapter represents only a guide to the teaching of marine geology and is not a comprehensive coverage. It purports to outline some of the main concepts covered in marine geology;

it should be used with the listed references so that a more detailed and comprehensive understanding of any single conept can be made. The exciting feature of marine geology is its youthfulness, the many unknowns and problems that remain to be solved, and the challenge it presents to geologists both to obtain and to understand the significance of samples from the sea floor.

Since man first launched boats and sailed on the waters of the sea he has tried to discover what lay beneath the sea. Some knowledge of the depths of coastal waters was quickly accumulated, but nothing of the deep sea bottom was known until very recently, although attempts to sound the bottom have been recorded. Magellan tried to sound the bottom of the Pacific, but as he only had 200 fathoms of rope he was unsuccessful. By the early 19th century geologists were aware that the continents were rimmed by a shallow region of sea floor with a steep lip descending to unknown depths. The 1840 Sir James Clark Ross made the first deep sounding, using hemp rope, and recorded a depth of 2425 fathoms in the South Atlantic.

In 1872-76 the famous Challenger Expedition took place and the first comprehensive collection of samples from the deep sea was made. These were studied and described by Sir John Murray, one of the naturalists aboard the Challenger and later the director of the Challenger Office, in collaboration with the Belgian mineralogist the Abbe Renard, and together they published the first general description of the deep sea floor in 1891 as the penultimate volume of the Challenger Reports. After the Challenger Expedition many other voyages were made on which soundings and samples were taken. However, the process of taking lead line soundings was laborious and time consuming and knowledge of the nature and topography of the sea floor accumulated slowly.

During World War I, the technique of determining the depth by echo-sounding was developed. In 1927 the German vessel Meteor made the first full scale expedition using the new technique and the detailed nature of the sea floor at last began to be revealed. Until this voyage, in spite of the many isolated soundings made, most geologists thought of the sea floor as essentially flat and regular with only a limited number of features.

Since the Meteor, many navy and oceanograhic institution vessels of different countries have continued to map the sea floor and collect samples. The extent of flat, regular features shown on maps has gradually decreased and now good and relatively accurate maps of the major features of the sea floor are available (see References and Figures 1 and 2).

In addition to our growing knowledge of the topographic features of the sea floor, the many samples of rocks and sediments recovered have increased our understanding of the nature of the ocean floor and the processes occurring on it. Geophysical measurements have greatly increased our knowledge of the structure and properties of the earth's crust beneath the sea. Some aspects of the various tools used and measurements made by geologists are discussed in a separate section at the end of this chapter.

Surface Features of the Ocean Floor

The earth's surface is very irregular with a difference of 20 km betweem the deepest and highest points. Because of gravity, water accumulates in the low areas and covers most of the earth's surface, approximately 70% in fact, or 510 x 10^6 km^2. The continents and their islands divide the hydrosphere into three oceans; a natural boundary is not present in the southern hemisphere where the Antarctic waters connect the Pacific, Indian, and Atlantic Oceans. The three oceans can be considered to begin at the southern tips of the three main land masses. Adjacent seas are formed where land masses or island chains separate certain oceanic areas from open ocean - they are called marginal seas where they form an identation in the continental coast, and mediterranean seas when they are enclosed to a large extend by hand.

For the oceanographer, the main interest in the topography of the sea floor is that it forms the lower and lateral boundaries of the water. The presence of land barriers, submarine ridges, or other features that impede the free flow of water will affect the patterns of circulation and properties of water masses, and the distribution of marine organisms. The geologist is concerned with the topography of the sea floor because features on the earth's surface are often an expression of forces taking place, or having taken place, in the earth's interior, and the nature and distribution of sediments on the sea floor is closely related to the topography.

A common method of representing the character of the relief of the earth's crust is to use a hydrographic curve - this is simply a curve or graph showing the area of the earth's solid surface above any given level of elevation or depth. Such a curve is shown in Figure 1. It should be noted that the hydrographic curve is not an actual profile of the land surface and the sea bottom because it represents merely a summation of areas between given depth levels without reference to their location or the spatial relationship of elevations and depressions. Actually the highest mountains are commonly near the coasts, and the deepest depressions near the continental margins and not as shown in the hydrographic curve. In general, the frequency distribution of the depth interval is the same in each of the three oceans. Four of the main morphological zones of the oceans are represented in the hydrographic curve - deep-sea trenches, deep-sea basins, the continental slope, and the continental shelf.

Good physiographic diagrams are now available (see References) and should be used to indicate the variability of topography and the relations of the main morphological features. Figures 2 and 3 exemplify these aspects. Some of the major features are discussed below.

A. Trenches

These are narrow, often arcuate depressions, most of which are situated on the landward edge of the structural limits of the deep-sea basins. Figure 4 shows the distribution and names of some of the principal deep sea trenches. The deepest points of the sea are found in these trenches - 11,500 meters in the Mindanao Trench, 11,000 meters in the Marianas Trench, and 10,800 meters in the Tonga Trench. The trenches often occur on the deep ocean side of island arcs, and border parts of the western coasts of North and South America. Seismic studies indicate that the trenches coincide with zones of very frequent earthquakes.

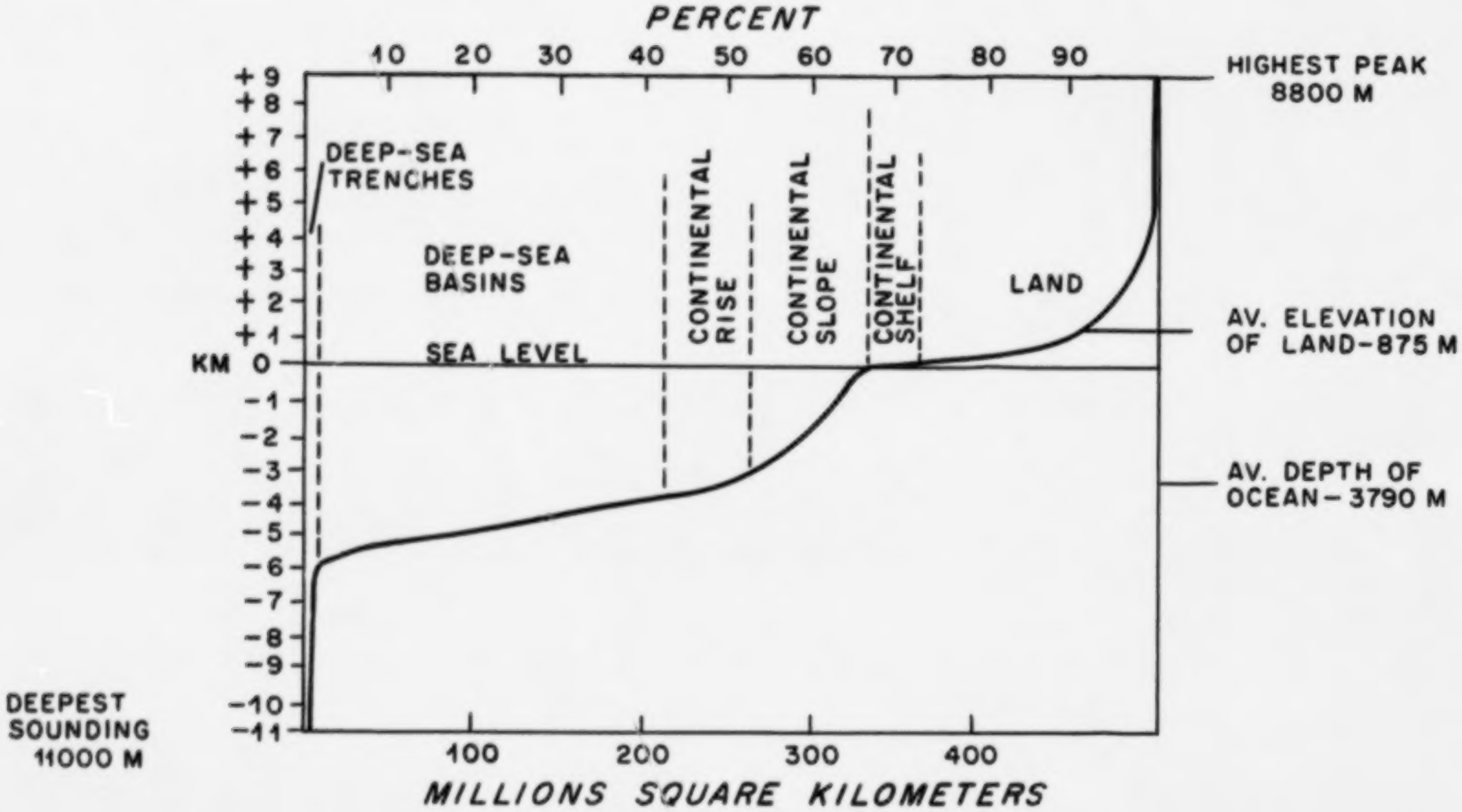


Figure 1. Hypsographic curve of earth's crust showing main topographic features.

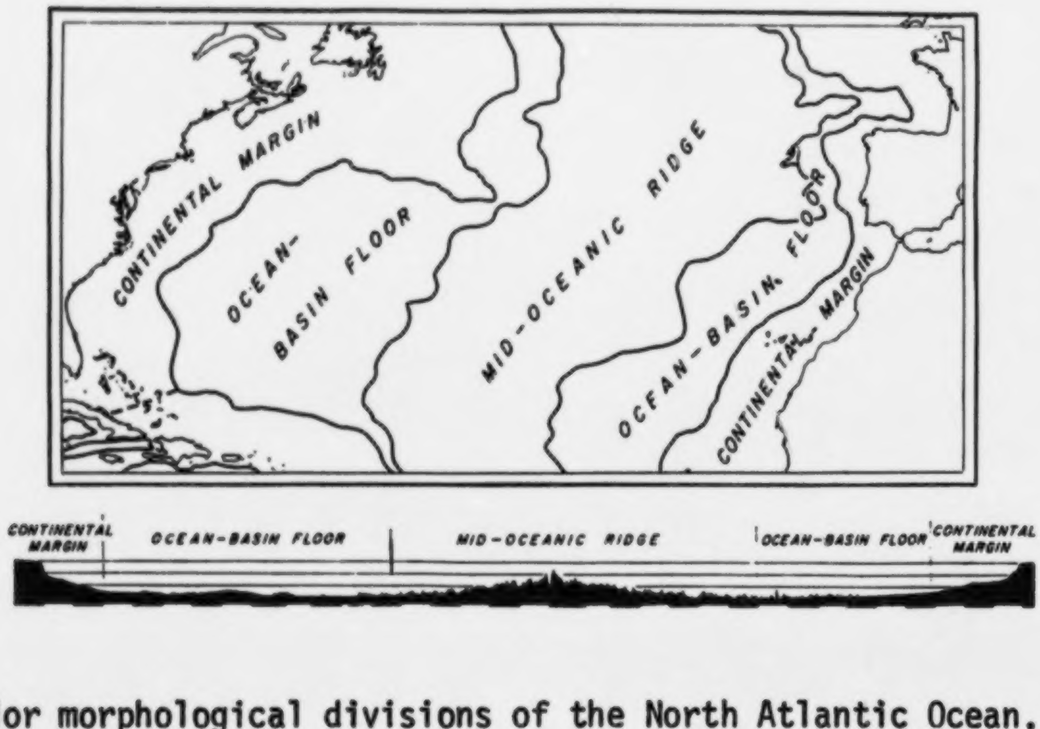

CONTINENTAL MARGIN
OCEAN-BASIN FLOOR
MID-OCEANIC RIDGE
OCEAN-BASIN FLOOR
CONTINENTAL MARGIN
CONTINENTAL MARGIN
OCEAN-BASIN FLOOR
MID-OCEANIC RIDGE
OCEAN-BASIN FLOOR
CONTINENTAL MARGIN

Figure 2. Major morphological divisions of the North Atlantic Ocean. The profile is a representative profile from New England to the Sahara Coast. (From Heezen and Menard, 1963. Reproduced by permission.)

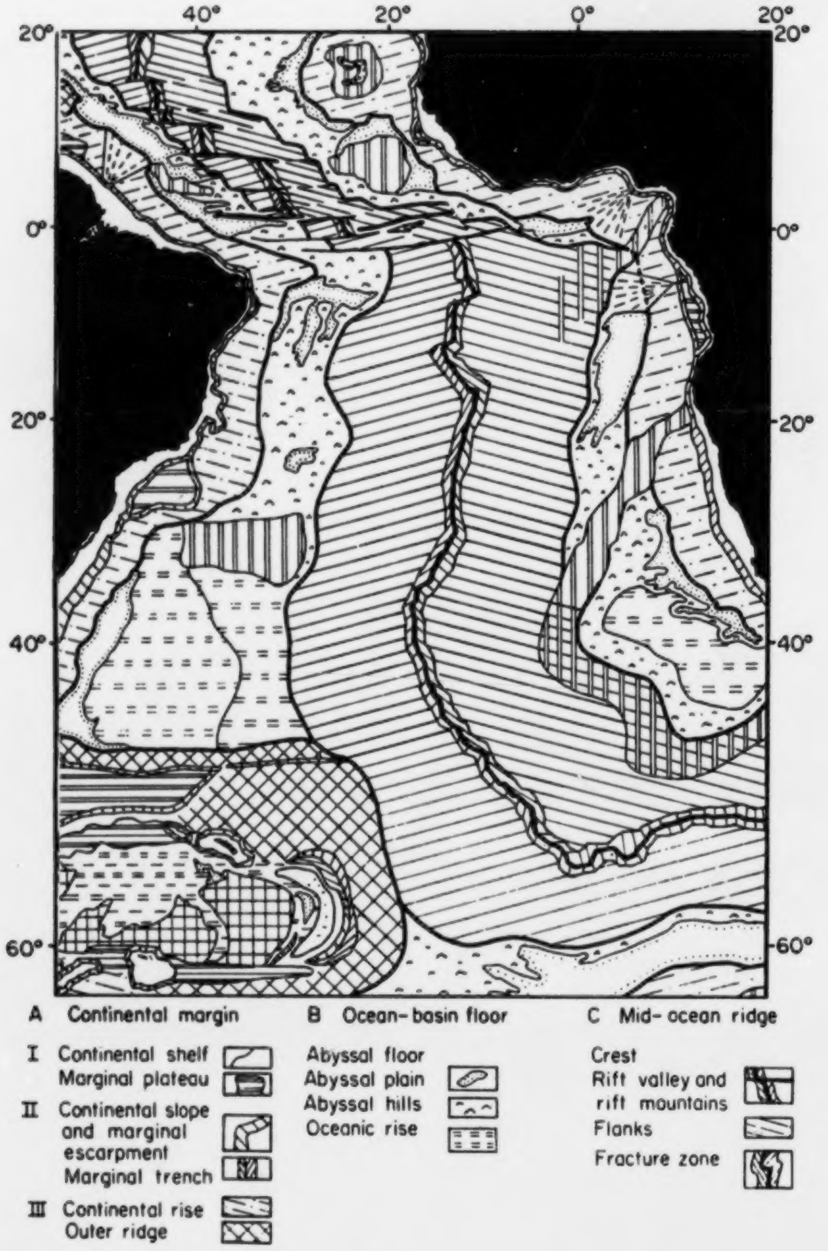

40°
20°
0°
20°
20°
0°
20°
40°
60°
A Continental margin
I Continental shelf
Marginal plateau
II Continental slope and marginal escarpment
Marginal trench
III Continental rise
Outer ridge
B Ocean-basin floor
Abyssal floor
Abyssal plain
Abyssal hills
Oceanic rise
C Mid-ocean ridge
Crest
Rift valley and rift mountains
Flanks
Fracture zone

Figure 3. A generalized province map of the South Atlantic showing the threefold division of the ocean into continental margin, ocean-basin floor and mid-oceanic ridge. In the equatorial Atlantic a series of left slip faults or fracture zones has offset the mid-oceanic ridge westward for over 2000 miles. Although fracture zones have been known since 1939 in the Pacific, this is the first time that they have been mapped in the Atlantic. (From Heezen and Ewing, 1963. Reproduced by permission.)

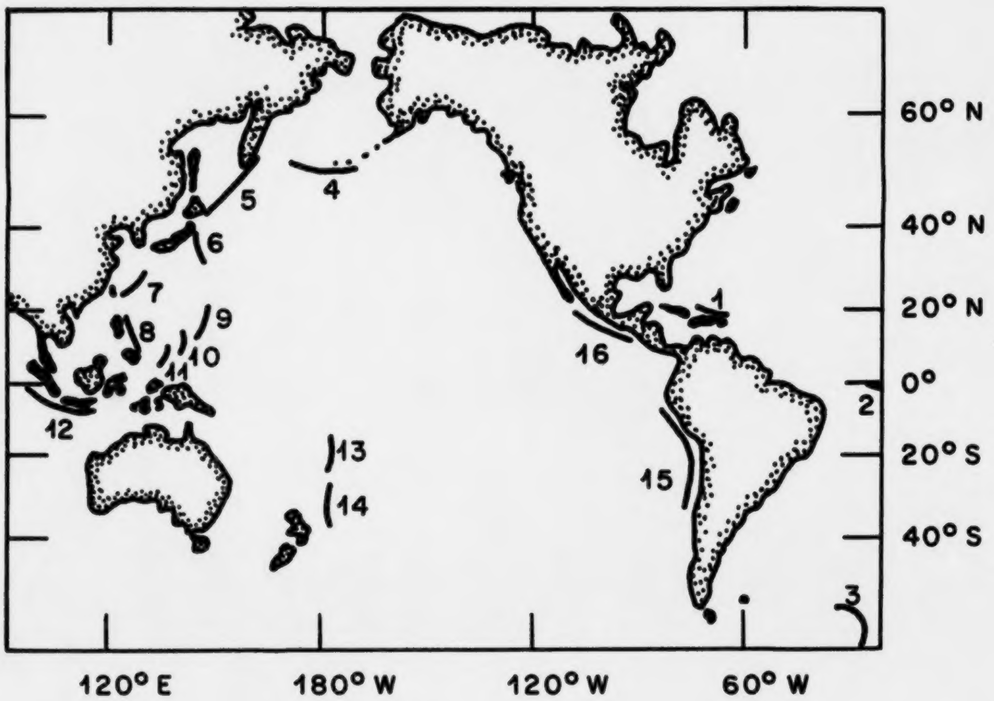

60° N
40° N
20° N
0°
20° S
40° S
120° E
180° W
120° W
60° W
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Figure 4. Diagram showing location of some major deep-sea trenches. Numbers refer to following trenches:

1. Puerto Rico
2. Romanche
3. South Sandwich
4. Aleutian
5. Kurile
6. Japanese
7. Riu Kiu
8. Mindanao
9. Marianas
10. Yap
11. Pelew
12. Sunda
13. Tonga
14. Kermadec
15. Peru and Chile
16. Middle American

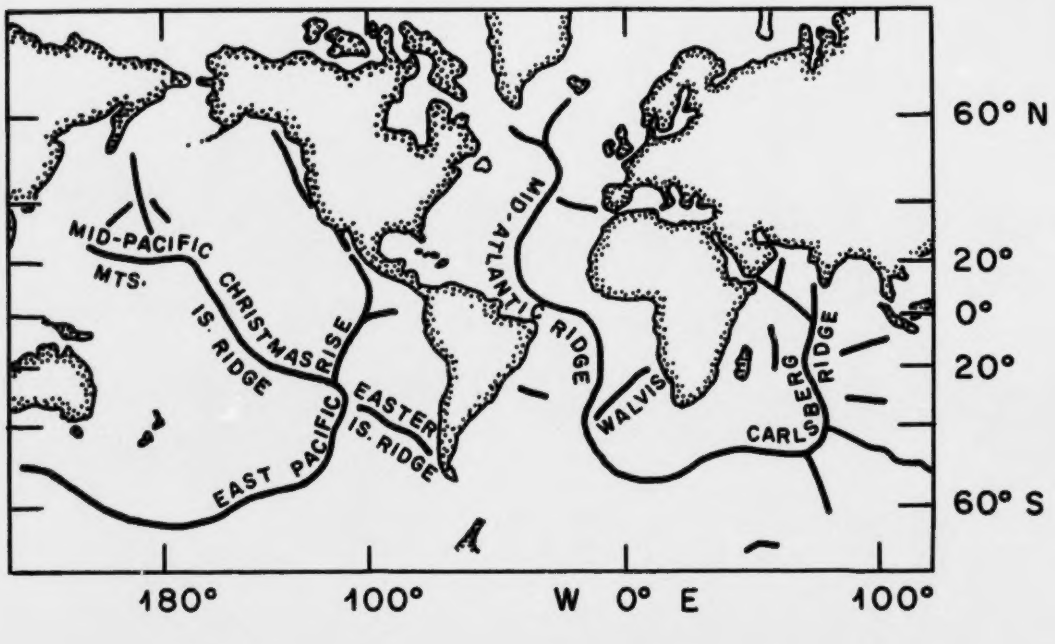

MID-PACIFIC
MTS.
CHRISTMAS
IS. RIDGE
RISE
EAST PACIFIC
EASTER
IS. RIDGE
MID-ATLANTIC
RIDGE
WALVIS
CARLSBERG
RIDGE
60° N
20°
0°
20°
60° S
180°
100°
W 0° E
100°

Figure 5A. Mid-oceanic Ridges of the World Oceans shown diagrammatically.

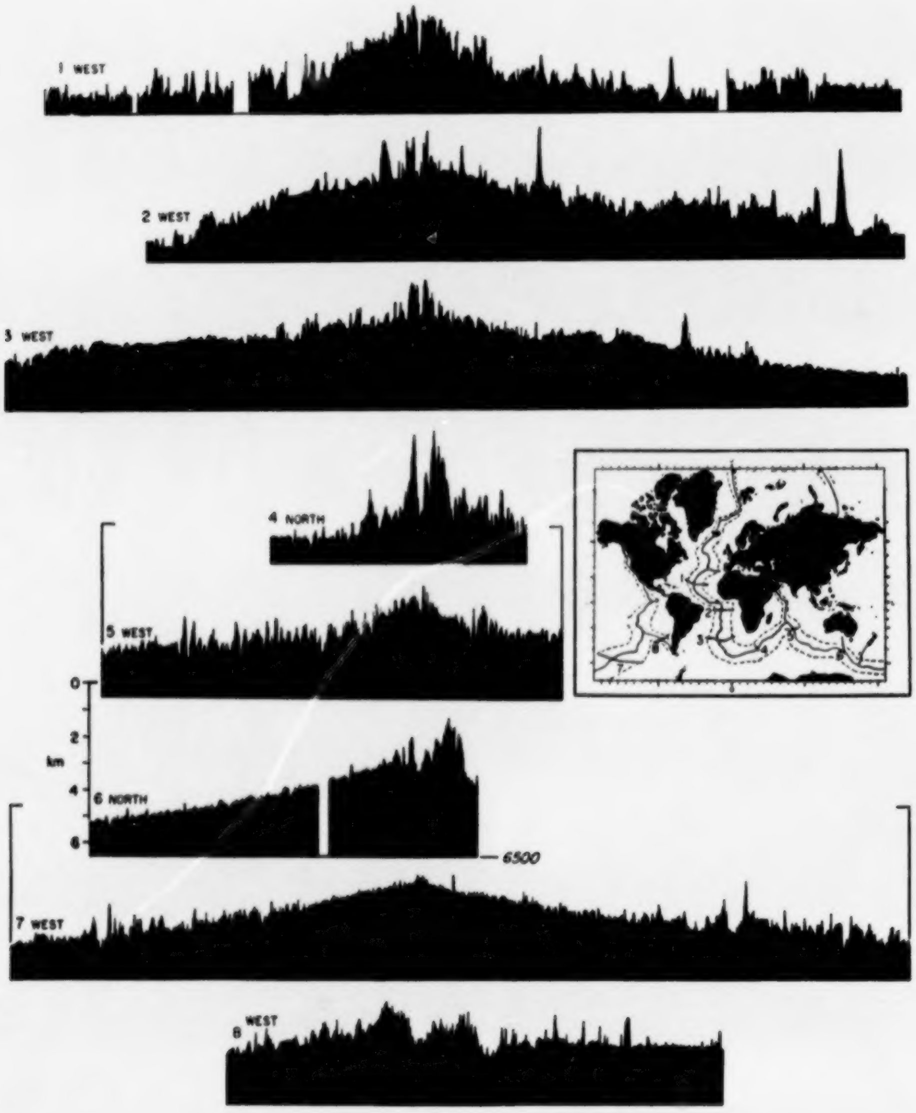


Figure 5B. Eight typical profiles of the mid-oceanic ridge in the North Atlantic, South Atlantic, Indian and South Pacific Oceans. The smooth relief across the crest of the mid-oceanic ridge in the South Pacific contrasts markedly with the rougher topography of the other oceans. Profile 2 was obtained aboard CRAWFORD and Profile 8 was obtained aboard HORIZON. The remaining profiles were obtained with a Precision Depth Recorder aboard R.V. VEMA. Vertical exaggeration of profiles is 100:1. (From Heezen and Ewing, 1963. Reproduced by permission.)

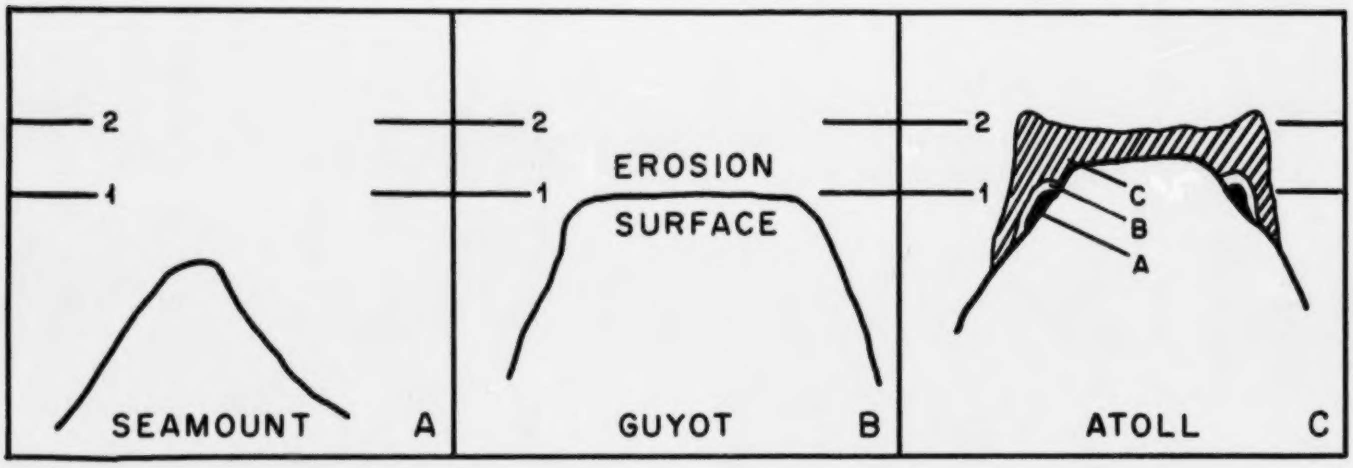


Figure 6. Diagrammatic profile of a seamount (A), a guyot (B), and an atoll (C). Number 1 refers to past sea level, number 2 to present sea level. In diagram C, A. represents fringing reef
B. a barrier reef
and C. present day atoll

B. Ridges

One of the surprising discoveries of recent marine geologic studies has been that each of the oceans has a large ridge running almost centrally throughout. Many of the ridges are major relief features of the earth as a whole, rising more than 5000 meters above the adjacent sea floor and being more or less continuous for up to 60,000 kilometers. Figure 5 indicates the main features of the system. Not all the ridges are centrally located with respect to the ocean, though major portions of them are, nor are they all similar in topography. They range from broad, gently sloping rises to steep, narrow, rough topography. In the North Pacific, the ridge system consists of many narrow, steep sided submarine mountains; in the Southeast Pacific, broader and less rugged topography predominates. The Mid-Atlantic Ridge and the Mid-Indian Ocean Ridge are characterized by elongate, narrow, steep sided features and they are occassionally seen above the sea surface as oceanic islands.

Numerous "fractures" or "offsets" of the axis characterize the ridge systems. Volcanic activity and earthquakes commonly occur along the ridge axis. In many parts of the system the ridge axis is marked by a central valley - often termed the "central rift valley."

C. Seamounts and guyots

Submarine hills and mouhtain features have been discovered on many parts of the ocean floor. Two of the most spectacular and common forms are known as seamounts and guyots. These submarine features have a relief of 3000 meters or more - guyots being distinguished from seamounts by their flat tops (see Figure 6). There seems little doubt that both are formed from volcanoes errupted beneath the sea - they are generally circular in plan and steep sided, and volcanic rocks have been dredged from the sides of many. There are estimated to be 10,000 such structures in the Pacific Ocean, and theycommonly occur in the other oceans.

The flat plateaus of the guyots are believed to have been formed by erosion in shallow water or even above water. Many of the seamounts have shallow water sediments or corals on their summits. However, the tops of both the seamounts and guyots are often 1000 to 2000 meters below the present sea level. The shallow water features of their summits could be accounted for by a drastic change in sea level in the past, but most geologists do not believe such large fluctuations in sea level occurred. They argue that the seamounts and guyots may have been close to, or even above, the sea surface once and have since subsided. Other evidence that subsidence did occur comes from studies of the coral structures found on the summits of some seamounts and guyots; this is discussed below.

D. Coral reefs and atolls

The distribution of coral reefs and atolls in the oceans is primarily determined by water temperatures suitable for coral growth. Coral reefs require relatively warm water and are thus restricted geographically to the middle latitudes or the 20°C isotherm. Reefs are of various kinds and are often found on seamounts; they are termed fringing or barrier reefs depending on their position and development state (see Figure 6). Coral atolls consist of a ring of coral reef growing actively on the seaward margin and enclosing a lagoon in the center. Atolls, which are most numerous in the Pacific, are found on the tops of guyots and seamounts.

The origin of coral atolls was once a problem which caused great debate amongst geologists. Charles Darwin believed that the atolls were formed from the simple fringing reef that originally grew around an emergent island. This island subsequently subsided and a barrier reef was formed; as subsidence continued the coral growth maintained the same rate as the sinking island. Eventually the island submerged and a reef was left surrounding the lagoon that was located over the former position of the island. Other geologists believed that the seamount or guyot was either eroded by wave action or that a platform was built by deposition to a depth suitable for coral growth. The shape of the atoll with its lagoon was considered to be due to the fact that the reef building corals on the edge grew more vigorously than those in the center. Other geologists believed the shape resulted from changes in sea level during the glacial times. (See Chapter 3).

Recent deep drilling and seismic studies on atolls indicate that coral rock extends to great depths below the ocean, though it must obviously have started on a shallow platform. Darwin's hypothesis of sinking seamounts and guyots thus appears to be correct.

D. Continental margins

On the continental sides of the deep ocean basins and separating them from the continents are the features known as the continental rise, slope and shelf. For the purposes of this review they have been considered together in a separate section (Chapter 3). In fact they are an integral part of marine geology and the oceans, but they do have some unique features that can justify such an artificial separation.

Rocks of the Sea Floor

The oceans act as a large reservoir into which the products of the erosion of the continents are carried via rivers, glaciers, and winds (and recently by man). In addition, after death, the skeletons of many of the organisms living in the seas accumulate on the sea floor. All these rocks and mineral particles, including those derived from the organisms, constitute the sediments that cover most of the ocean floor.

Parts of the sea floor, particularly steep slopes such as seamounts or parts of the mid oceanic ridges, are not covered by sediments, and large rock masses are exposed. These are igneous rocks formed by solidification from a molten or partly molten state.

Some characteristics of the sedimentary and igneous rocks found on the sea floor are further discussed below.

A. Igneous rocks

Geologic studies of the oceanic islands - which are actually portions of the sea floor sticking above the sea surface - indicate that they are volcanic in origin. They are made up of vast lava flows piled up on each other. Hawaii is a classical example. Occassionally, new islands will suddenly and dramatically appear above the surface as submarine volcanoes erupt. Surtsey, near Iceland, born in 1963, is a good example.

Dredging of the sea floor on the sides of seamounts or on the ridges has also recovered mainly volcanic rocks. In the case of the ridges, some of these rocks have been erupted from large, circular volcanoes, but others from large fissures in the sea floor.

These volcanic rocks are basalts - basic rocks relatively low in silica and alkalies and rick in magnesium. Mineralogically they are predominately olivine, pyroxene, and plagioclase. None of the sialic rocks commonly found on the continents - that is, rocks rich in silica and alkalies, such as granite - are found on the ocean floor. This is an important observation and one that is pertinent to our understanding of the differences between ocean basin and continental structure.

There is one exception to the observation that all oceanic islands are volcanic - the Rochedos Sao Pedro é Sao Paulo (St. Paul's Rocks). These are located about 80 kilometers north of the equator in the middle of the Atlantic. Darwin, during the voyage of the Beagle in 1831, first recognized their uniqueness. They are composed of an ultrabasic rock called peridotite, which is a type of rock that is lower in silica and richer in magnesium than the basalts and composed principally of olivine and pyroxene. Dredge hauls in the deep fissures of the ridges and deep in the trenches have also recovered ultrabasic rocks.

These ultrabasic rocks appear to underlie the volcanic rocks in many parts of the sea floor, but how widespread they are is not certain. Of great interest to geologists is the relationship between the volcanic and ultrabasic rocks, and since the ultrabasic rocks were formed deep in the earth they offer clues to our understanding of the earth's interior.

B. Sediments

The major part of the deep ocean floor is blanketed by a sedimentary cover. The type and thickness of sediment varies dependent on the source and the environment. Some aspects of the types of sediments and their distribution are discussed below.

1. Source and composition

The sediments can be classified into four main components, excluding the water trapped between the particles:

a. Terrigenous

These are deposits whose principal components are derived from land erosion and volcanic debris of subaerial or submarine origin. These deposits are very often termed "red clay," but that is really an erroneous term since the color of many of these deposits is not red but may vary from gray to green. Moreover, when there is a red color it is actually due to the presence of a non-terrigenous component. The lithogenous deposits are generally very fine grained, often with a median grain diameter less than 2 microns. They are composed principally of clay minerals with some quartz and feldspar. Where volcanic debris is present, other minerals such as olivine or pyroxene may be found. The terrigenous sediments are carried into the oceans principally by rivers, glaciers, or winds, and they eventually sink to the bottom.

b. Biogenous

These sedimentary components consist of the remains of organisms, including the hard, inorganic skeletal parts. When these components comprise greater than 30% of a deposit, the sediment is termed an ooze. Planktonic animals and plants, or at least their hard-to-dissolve residue, often the skeletal or shell portion, are the dominant organisms comprising the biogenous deposits. The chemical composition and mineralogy of the skeletal parts determines the type of biogenous sediment:

i. Calcareous oozes

Predominantly composed of calcium carbonate ($CaCO_3$) in the form of tests and skeletons, they are named according to the dominant organism present. Typically they include: (a) foraminiferal ooze, which is composed of the tests of planktonic Foraminifera ranging in size from 10 to 400 microns (Globigerina species are common); (b) coccolith ooze, which is composed of the cast plates of the planktonic algae Coccolithiphoridae ranging in size from 10 to 20 microns; and (c) pteropod ooze, which is composed of the tests of the pelagic molluscs called pteropods - they are large in size, ranging from 1 to 10 millimeters. Corals, sponges, echinoids, and crinoids also form a minor part of the deep sea calcareous oozes.

ii. Siliceous oozes

These deposits are composed of opal - a highly disordered form of silicon dioxide containing bound water and originating as the skeletons or frustules of plants and animals. The two main types are: (a) diatom ooze, which is composed of the frustules of planktonic siliceous algae belonging to the phytoplankton; and (b) radiolarian ooze, which is made up of the highly complex and ornate siliceous skeletons of planktonic protozoa.

iii. Apatite

These are deposits containing calcium phosphate of biological origin. They are a minor phase in deep sea deposits. The principal components are fish teeth and whale carbones.

c. Hydrogenous

These are the components of deep sea deposits formed by inorganic precipitation from sea water. Varieties found include:

i. Ferromanganese minerals

These are often found in the form of discrete nodules. Sometimes they occur as a coating on grains or rock surfaces. The red color of the "red clays" is due to the presence of these minerals. They are formed by the accretion of colloidal forms of hydrated oxides of iron and manganese. They also accumulate other elements from sea water, such as nickel, cobalt, copper, molybdenum, lead, and zinc, and thus represent quite a valuable ore deposit. They are found covering extensive areas of the sea floor in the Pacific and other oceans.

ii. Phillipsite

The aluminosilicate zeolite mineral phillipsite is a significant component in some deep sea deposits, particularly in the Pacific Ocean. It is often associated with volcanic minerals and the degradation of these products by the sea water may provide the environment for the precipitation of phillipsite.

iii. Carbonate

Inorganic precipitation of calcium carbonate is known to occur. It is sometimes found in the deep sea on the sides of seamounts and on mid-ocean ridges, often cementing the biogenous carbonate tests together.

d. Cosmogenous

Small spherical particles about 0.2 millimeters in diameter have been found in pelagic deposits. They are compositionally very similar to the iron-nickel meteorites and are believed to be of similar extra-terrestrial origin.

Figure 7 summarizes the principal sediment types, and their sources and pathways in the ocean.

2. Sediment distribution

The final distribution and composition of bottom sediments is a function of a number of controlling factors.

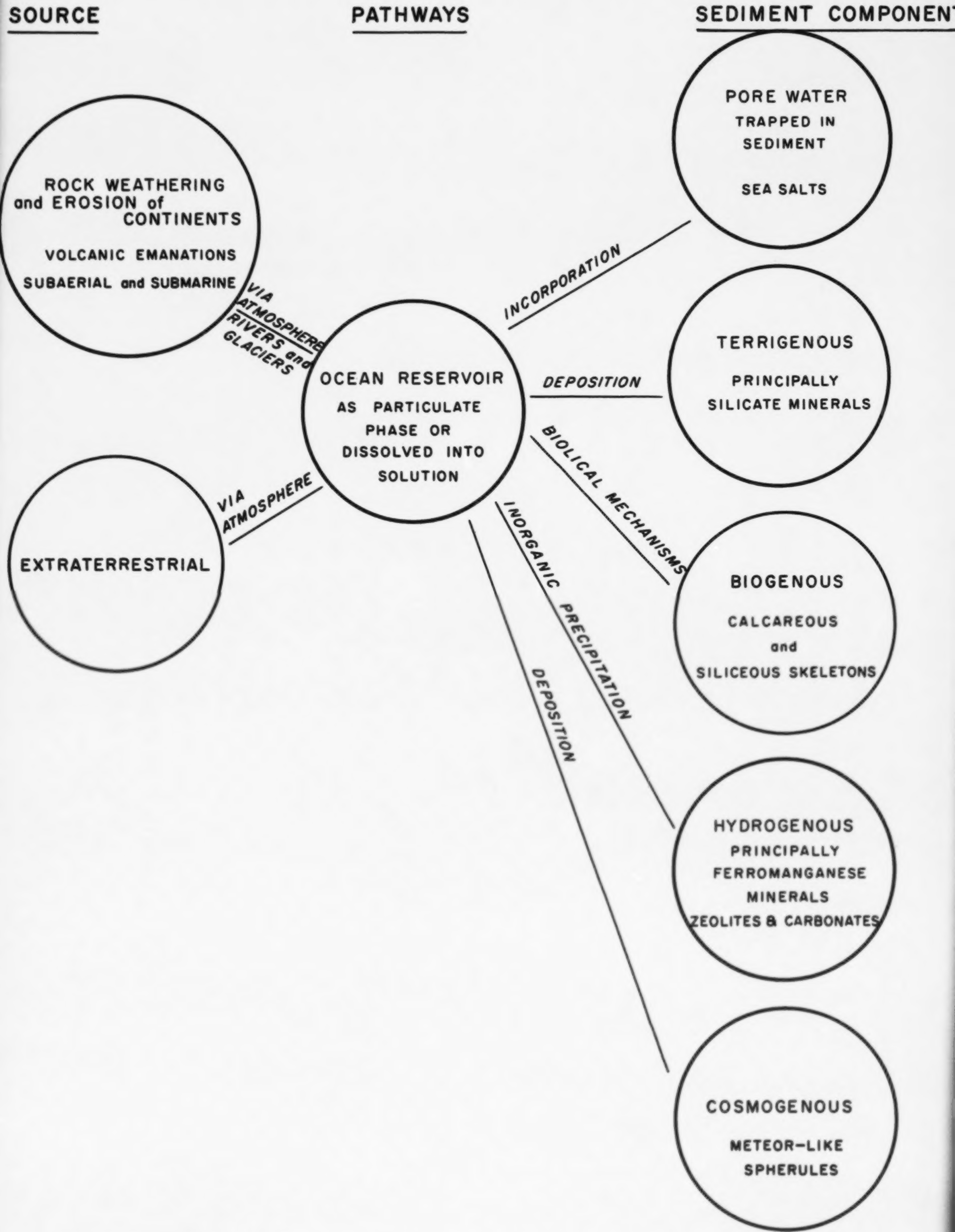

SOURCE
PATHWAYS
SEDIMENT COMPONENT
ROCK WEATHERING and EROSION of CONTINENTS
VOLCANIC EMANATIONS
SUBAERIAL and SUBMARINE
VIA ATMOSPHERE
RIVERS and GLACIERS
EXTRATERRESTRIAL
VIA ATMOSPHERE
OCEAN RESERVOIR
AS PARTICULATE PHASE OR DISSOLVED INTO SOLUTION
INCORPORATION
DEPOSITION
BIOLICAL MECHANISMS
INORGANIC PRECIPITATION
DEPOSITION
PORE WATER
TRAPPED IN SEDIMENT
SEA SALTS
TERRIGENOUS
PRINCIPALLY SILICATE MINERALS
BIOGENOUS
CALCAREOUS and SILICEOUS SKELETONS
HYDROGENOUS
PRINCIPALLY FERROMANGANESE MINERALS
ZEOLITES & CARBONATES
COSMOGENOUS
METEOR-LIKE SPHERULES

Figure 7. Schematic view of the source and pathways of marine sediment components.

a. Source

The mineralogy and relative abundance of the terrigenous components vary depending on the geology of the land masses from which they are derived. The mineralogy of clays found in the deep sea shows definite latitudinal effects. In high latitudes glacially derived components predominate; in middle latitudes the deep sea sediments contain components typical of the arid and leached soils of the equatorial countries. Quartz grains may be found far out at sea where winds blow from desert regions over the ocean, as off northwestern Africa.

Biogenous components vary according to the distribution of the planktonic species in the surface waters. They are most abundant in areas of high productivity.

b. Physical

The rain of particles settling through the water column falls at a rate dependent on their size and density, and the particles are subject to transport as a result of horizontal water movements. The processes such as fall velocity, ocean currents, and transport along the bottom which determine the particle size of a sediment strongly influence the distribution of sediment types. The coarse grained and dense terrigenous particles are generally deposited close to their source; lighter particles, particularly those that are wind borne, are carried out farther. Some of the coarse grained terrigenous deposits are not confined to the continental margins but may be found many hundreds of miles out in the deep sea basins. These deposits are believed to have been emplaced by turbidity currents. These currents originate on the continental slope; when the bottom layers of water become charged with sediments, and thus become more dense than the surrounding water, they rush downslope. Though the sediments are deposited in deep water, their true origin may be recognized by their shallow water fauna and by the presence of graded sand beds (the larger and heavier particles at the base of the bed).

Biogenous deposits are often of larger grain size than the clay sized terrigenous components of the deep sea. They may not be carried far in a horizontal direction from their source even when strong currents exist. Some sorting of the larger and smaller sized components may take place, however.

c. Chemical

The sediment particles are subject to chemical changes by reaction with the surrounding water. Biogenous components may often completely dissolve. Calcium carbonate solution generally increases with increasing pressure and decreasing temperature. Deep waters thus often dissolve carbonates, and deposits of them may not be found at depths exceeding 5000 meters. The distribution of hydrogenous components is dependent on the chemical character of the water mass of any region.

Figure 8 indicates the present distribution of sediments at the sea floor-water interface. This diagram delimits the major zones in which a certain type of deposit predominates, although other types may be present. From the diagram it is apparent that the siliceous oozes are restricted to high and low latitudes and areas of upwelling; diatom oozes occur in the Antarctic and a belt across the North Pacific, and radiolarian ooze is found in the equatorial Pacific and in the zones of upwelling off the coasts of Peru and southwestern Africa. Carbonates are not found in the deep ocean basins. Corals are restricted to the middle latitudes or 20°C isotherm.

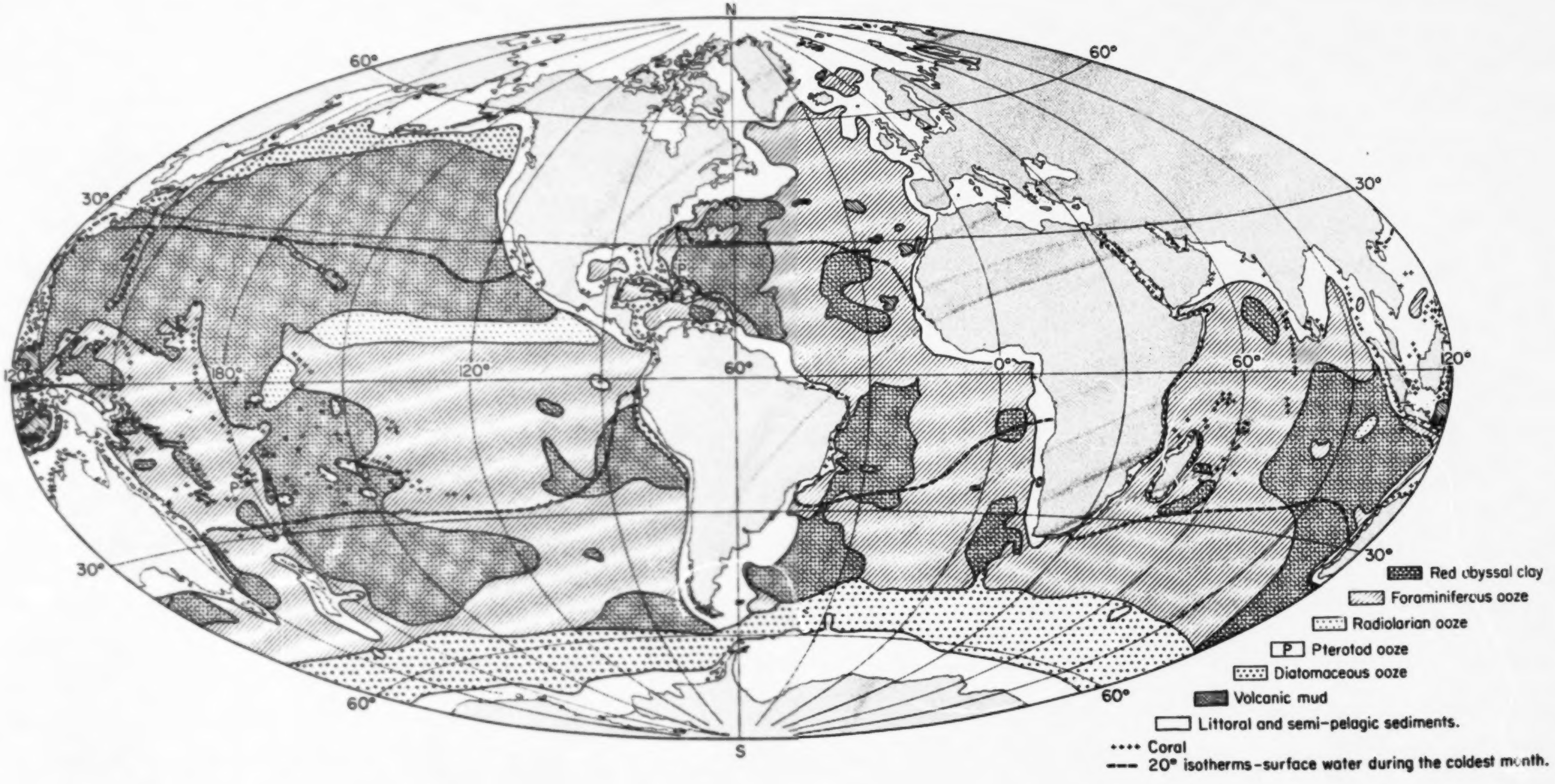

N
S
60°
30°
0°
60°
120°
180°
120°
30°
60°
Red abyssal clay
Foraminiferous ooze
Radiolarian ooze
P Pterotod ooze
Diatomaceous ooze
Volcanic mud
Littoral and semi-pelagic sediments.
Coral
20° isotherms-surface water during the coldest month.

Figure 8. Sediments of the World Oceans. (From Dietrich, 1957. Reproduced by permission.)

3. Importance

Sediment deposition in the deep ocean is relatively slow in regions not disturbed by turbidity currents or by tectonic activity. Paleontological and radioactive measurements indicate that rates of deposition are about 1 to 2 centimeters per 1000 years for the biogenous oozes and less than 0.5 centimeters per 1000 years for the terrigenous deposits. Thus, a short, uninterrupted sample of sediment, as is taken by piston corers (see page 36), reveals a relatively long sequence of history. Changes in the composition of the different sediment components, or their relative amounts, are indicative of past environments and conditions.

The biogenous components are particularly indicative of climatic conditions. The zones of relative distribution of temperature sensitive plankton forms indicate changes in temperature of past surface waters. Paleoclimates and surface temperatures may be inferred from changes in species or morphology of species (e.g,, the direction of coiling of the shell of one species of Foraminifera varies with temperature), and from oxygem isotope measurements in the calcite of the carbonate tests (the relative proportions of the different oxygen isotopes is dependent on the temperature of the water in which the calcite was formed). Changes in the thickness of the biogenous sequences may either reflect changes in the ocean current systems and areas of upwelling and biological productivity, or changes in bottom water composition such that more or less skeletons were dissolved.

Changes in the terrigenous components may reflect changes in transporting agencies. Sea level changes may cause more or less erosion of land and littoral areas. Glaciation may bring new deposits into the seas. Volcanic episodes may be marked by ash layers in the sedimentary sequence. Changes in the hydrogenous components may reveal changes in the composition of water masses.

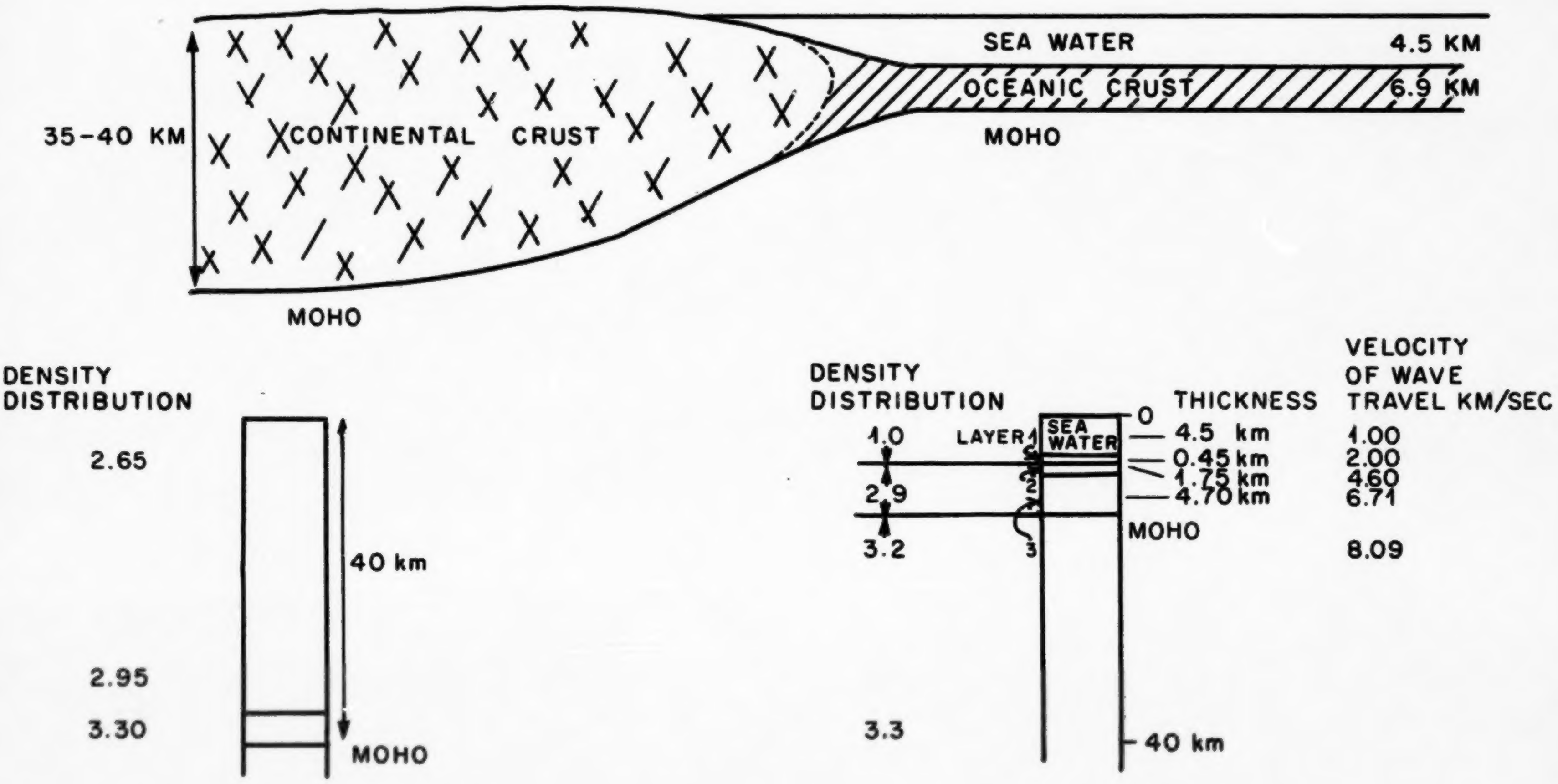
The Earth's Crust Beneath the Sea

The oceanic crust and the continental crust differ in thickness and composition. The crust is defined as the depth to the Mohorovičić discontinuity was recognized in 1909 by a Yogoslavian seismologist, Mohorovičić, and marks the position in the earth where the speed of a primary earthquake wave (ρ wave) suddenly increases from approximately 6.7 kilometers per second to 8.1 kilometers per second.

The continental crust is complex with layers of different density, which are, however, always in regular sequence. Generally, the continental crust is characterized in the upper portions by low velocity ρ waves and rocks of fairly low density - properties similar to those of granitic materials. The lower portion has higher velocity ρ waves and rocks of greater density. The total thickness varies, but the average thickness is about 35 kilometers.

In oceanic areas, the Moho is only 10 to 12 kilometers below the sea surface, or about 6 kilometers below the sea floor. With the exception of a thin layer of sediment, the oceanic crust is characterized by fairly dense rocks. Figure 9 shows the average crustal structure. Three horizontal layers are characteristically found in the crust of the ocean basins. Layer 1 consists largely of the sediments of the ocean floor. Layer 2, from seismic velocity and density considerations, and from drilling, dredging, and volcanic ejecta, appears to be principally composed of volcanic rocks. The composition of Layer 3 and the nature of the mantle are as yet uncertain.

Note that in Figure 9 a comparison of an average 40 kilometers of continental and oceanic section indicates that they have very similar masses. This illustrates the concept of isostatic equilibrium of the earth's outer surface and indicates a gravitational equilibrium that controls the height of continents and of ocean floors in accordance with the densities of their underlying rocks.


SEA WATER
4.5 KM
OCEANIC CRUST
6.9 KM
35-40 KM
CONTINENTAL CRUST
MOHO
MOHO
DENSITY DISTRIBUTION
2.65
40 km
2.95
3.30
MOHO
DENSITY DISTRIBUTION
THICKNESS
VELOCITY OF WAVE TRAVEL KM/SEC
1.0
LAYER 1
SEA WATER
0
4.5 km
1.00
0.45 km
2.00
1.75 km
4.60
4.70 km
6.71
2.9
2
3.2
3
MOHO
8.09
3.3
40 km

ISOSTATIC BALANCE: 2.8 X 36
+ 3.3 X 4
= 114.0

1.0 X 4.95
+ 2.9 X 6.45
+ 3.25 X 28.6
= 116.6

Figure 9. General characteristics of average oceanic and continental crust.

The Origin and Permanency of Ocean Basins

Historically, the question of the origin and permanency of ocean basins has long been the center of discussion and controversy. Broadly stated, the problem is whether the odean basins and continents have remained more or less in their present positions throughout geological time, or whether the continents have, in fact, moved their relative positions on the earth's surface. In 1912, Alfred Wegener formulated a hypothesis of continental drift. He based his conclusion mainly on the striking resemblance between the Atlantic coastlines of South America and Africa and on fossil evidence for a land connection between Brazil and Africa. He suggested that all the continents may once have formed a single, huge land mass which subsequently broke up into pieces and drifted apart.

Arguments against this theory of continental drift were quickly riased. Some of the relative points were the following:

1. There are fundamental structural differences between the oceanic crust and that of the continents, and it appears physically impossible to have continents "drift" through the oceanic crust material.
2. If the continents did move, fresh oceanic floor should be exposed at the "stern" of the drifting continents and this is not in fact seen.
3. Forces sufficient to move the continents do not appear to exist.

Wegener and others argued that something other than mere coincidence was needed to explain the fact that the continental margins of South America and Africa fit together so well. Moreover, geologic evidence based on rock types and fossils indicated equivalent locations on each margin. This evidence, however, was not sufficient in itself to persuade most geologists and, particularly, to overcome their objections concerning the rigidity of the crust and the mantle. Recently, however, new measurements and investigations support the hypothesis of continents moving on

the earth's surface relative to each other. Some of the evidence favoring such movement involves:

1. Paleomagnetic measurements on the continents

The magnetic axes of minerals in sediments of different geologic ages on a continent are aligned differently. Since they should be aligned with the earth's magnetic field, either the continents have moved relative to the present position of the magnetic poles, or the poles have moved in the past. The patterns of paleoclimates, as inferred from fossil evidence, are in general agreement with the proposed paths of continents necessary to bring the magnetic axes in line. Relative movement of the magnetic poles to align the axes differs from continent to continent, and movement of the continents is required to explain the different alignments.

2. Magnetic measurements in the oceanic crust

Measurements of magnetic intensity and direction across mid-oceanic ridges have revealed symmetrical patterns aligned on either side of the ridge axis and made up of bands of material which are alternately magnetized in opposite directions. These patterns are thought to result from intrusions or eruptions of materials at different geologic times when the earth's polarity was reversed. The symmetry results from the fact that the material was originally erupted at the axis of the ridge, magnetically imprinted by the earth's polarity at the time, and then split and carried away from the ridges at a uniform velocity as new material was injected between the split portions (See Figure 10). Studies of magnetic polarity on continental eruptions have confirmed the changes in the polarity of the earth's magnetic field and radiometric dating of the reversals in oceanic rocks allows estimates of the spreading rates to be made. Measuzements indicate rates up to a few centimeters (2-6) per year - the rate varying in different ridge sections.

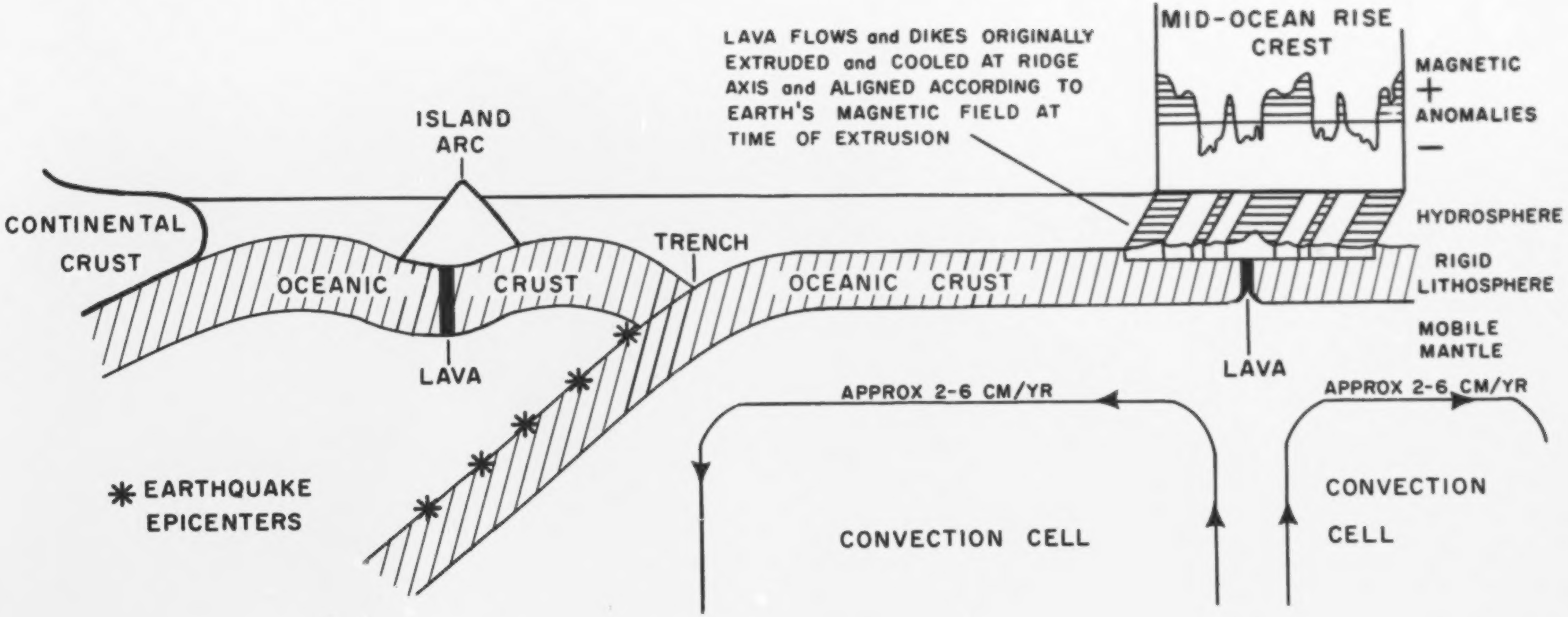

MID-OCEAN RISE CREST
LAVA FLOWS and DIKES ORIGINALLY EXTRUDED and COOLED AT RIDGE AXIS and ALIGNED ACCORDING TO EARTH'S MAGNETIC FIELD AT TIME OF EXTRUSION
MAGNETIC
+
ANOMALIES
—
ISLAND ARC
CONTINENTAL CRUST
TRENCH
HYDROSPHERE
OCEANIC
CRUST
OCEANIC CRUST
RIGID LITHOSPHERE
MOBILE MANTLE
LAVA
LAVA
APPROX 2-6 CM/YR
APPROX 2-6 CM/YR
✱ EARTHQUAKE EPICENTERS
CONVECTION CELL
CONVECTION CELL

Figure 10. Schematic view of the Sea-Floor Spreading Hypothesis.

3. Heat flow measurements

Anomalously high heat flow values are found in the ocean crust along the axes of mid-ocean ridges.

4. Earthquake measurements

By far the majority of earthquakes occur bordering many of the oceans and along ridge axes. Those at ridge axes are shallow in origin and indicate tensional forces. Those at ocean basin margins often originate deep in the mantle, sometimes in narrow, steeply dipping zones. The earthquake distribution is explained as the result of rifting at the ridge axis and downbuckling at the continental margins.

5. Sediment studies

The sediment thickness in the oceans is relatively small and, based on present rates, indicates deposition over a relatively short geologic time, not much more than 200 million years. The sediments thicken away from the axis of the ridge. The ages of the sediments indicated by paleontological studies of deep drilled samples are consistent with increasing age away from the ridge axis. Deep sea sediments are not found in continental regions - those marine deposits that present were apparently laid down in shallow or intermediate water or deep but narrow basins obviously bordering land.

All of this evidence is currently used to support a hypothesis of "sea-floor-spreading." New crustal material is injected at the ridge axis and the sea floor spreads out equally in either direction normal to the axis. The continents play a passive role and whole plates of the earth's crust are suggested to move relative to each other. Extension in one area is marked by downflow and compression elsewhere. The segments of the crust may override at the opposing margins and one side may be forced down to be reabsorbed in the mantle. This hypothesis differs from that of Wegener's in that the continents rather than actively drifting through the crust are analogous to logs frozen in ice. The plates of ice with the frozen "logs" are broken at certain places and the new ice forming at the break pushes the whole plate. In this analogy, the logs represent the continents, the ice represents the crust, and the water represents the particular region in the mantle beneath the crust and over which the continental plate is pushed. This is shown diagrammatically in Figure 10.

This hypothesis is one of the most exciting and dynamic aspects of marine geology at present. It should be emphasized, however, that it is only a hypothesis, and there remains much to explain. The forces driving the moving continental plates are not certain. One explanation favors convection in the mantle - the ridges representing a zone of upwelling and the plate margins a zone of downwelling as shown in the diagram of Figure 10. The explanation of the measurements and geologic observations in the oceans in terms of relative movements of segments of the earth's crust remains to be proved; as a working hypothesis it makes for exciting scientific investigation in marine geology.

Tools and Techniques of the Marine Geologist

The marine geologist is at a distinct disadvantage compared to his continental counterpart, as he is generally unable to select the samples he requires, or to measure their positions relative to each other or to submarine features. The marine geologist has to rely on specialized sampling devices to obtain the rocks and sediments from the ocean floor, and to use various geophysical measurements to infer the structure of the oceanic crust. The development of marine geology closely parallels the progress in oceanographic observational techniques. Some of the tools and techniques used in studying the geology of the ocean floor are briefly outlined below (details of technique and equipment can be obtained from most of the oceanographic texts listed in the references):

A. Geographic position

For each oceanographic observation a geographic position at sea must be determined. In most cases the astronomic method is used, in combination with "dead reckoning" using sextant, chronometer, compass, and log. These methods, however, are not always accurate enough for the geologist, particularly if he is trying to collect closely spaced samples. Radio-accoustical methods using directional radio beam are often employed, but they either lack the required accuracy or are not available in many parts of the ocean, particularly in the southern hemisphere. Satellite navigation using the artificial satellites riding the earth is currently being tried and promises to be the most accurate method of position determination. It is still in its infancy at present and only partial coverage of the oceans is available, but future years should correct this.

B. Measuring and representing relief

Wire and rope soundings of the ocean depths have been superseded by acoustic techniques. A sound beam of known frequency is emitted from a transducer so the return or "echo" of the sound from the sea floor is recorded and the time interval from ship to sea floor and back measured. The devices are normally set at a speed of sound in water of 800 meters per second. However, this method does not give the absolute depth because the speed of sound in sea water is not constant, but varies in response to certain properties of the water. Correction for the change in velocity depending on the salinity and temperature of the water column can be made and the depth calculated. Echo-sounding devices used today employ a continuous recording device so that a two dimensional profile and echogram, of the sea floor beneath the ship's rack is displayed (see Figure 11).

When sufficient two dimensional profiles are available in a given region, isobaths, or contours of equal depth, can be drawn through the profiles. This method allows the geologist to represent the three dimensional relief of the sea floor in two dimensions in a manner similar to the way elevation is indicated on contour maps used on land.

C. Sampling devices

The first bottom samples obtained from deep water were from the sounding leads used at the ends of ropes or piano wire. The leads had a cavity at the lower end filled with tallow to which bottom deposits adhered. Today the marine geologist has four basic sampling devices of which many varieties exist:

1. Corers

These are principally tubes, open at the lower end, which are used to cut sediment profiles of the ocean floor in much the same way as drills are used on land. Varieties used depend on whether the force driving the tube into the ocean floor is a heavy weight (in which case the instrument is called a free fall or gravity corer) or the pressure from an explosion. The length of the core may vary from one to thirty meters. The most favoured type used at present has an open pipe at the lower end of which is a tight fitting piston connected to the lowering wire. The pipe is suspended from a release mechanism and freed when a counterweight (often this is another small pipe which also serves to obtain a sample of the surface sediment) reaches the bottom. Heavy weights on the upper end of the coring tube drive the pipe into the sea floor. Sufficient wire is allowed so that the piston in effect remains immobile at the water-sediment interface and the pipe is driven over the piston into the floor. This results in the sediment's being drawn in by the effect of the piston at the same rate as that at which the pipe penetrates the bottom, and an undisturbed column of sediment is obtained.

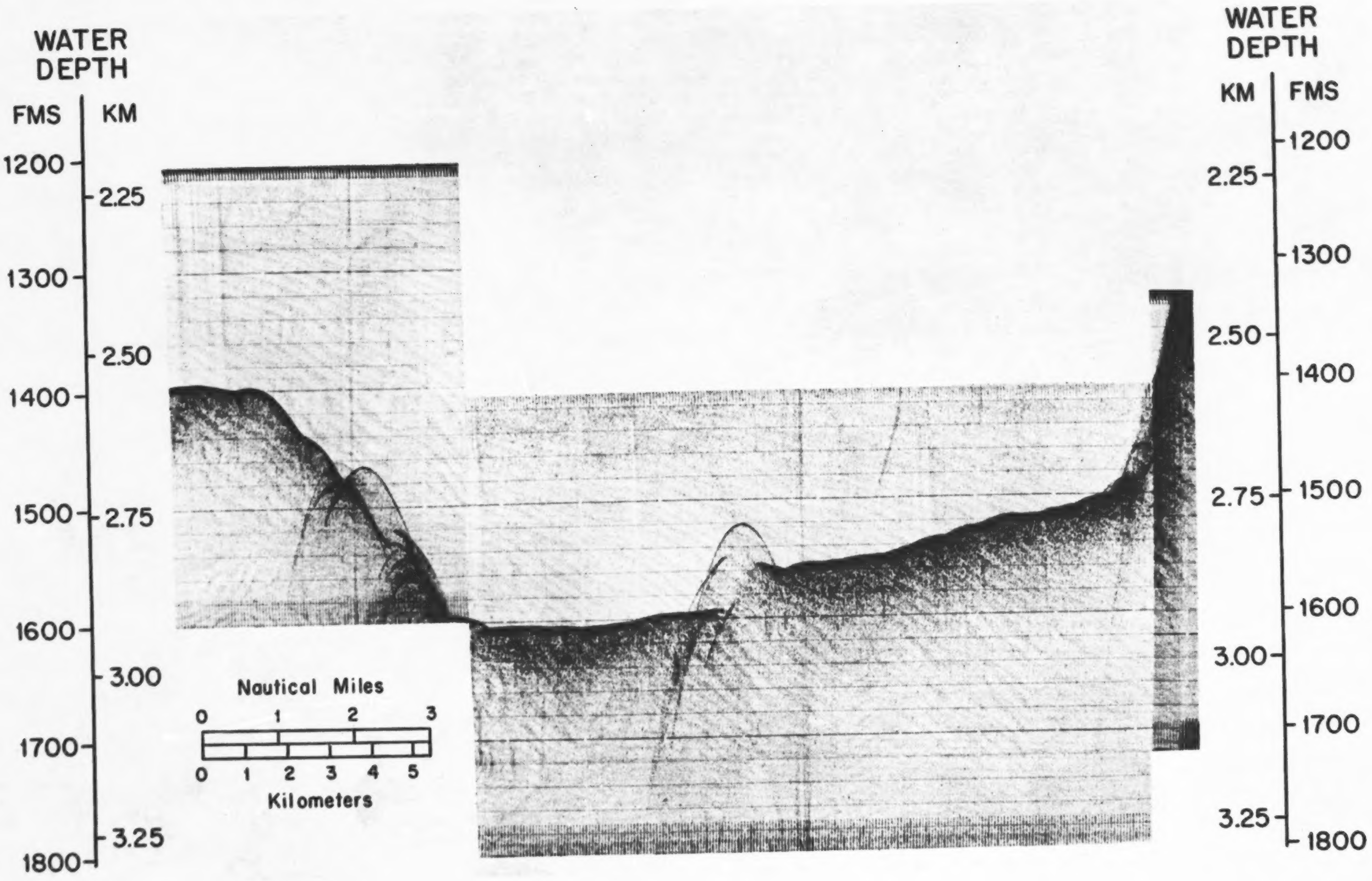


Figure 11. Record of a continuous echo-sounding bottom profile. Segments of the record have been readjusted to show correct scale.

2. Grabs and snappers

These are devices used to catch a portion of the bottom surface between jaws. Varieties exist from those that simply have two jaws to those that have multiple jaws. They can often be used on areas of the sea floor covered by coarse sediment which is not easily penetrable by coring tubes.

3. Dredges

These are devices generally used for recovering very course materials from the sea floor such as rock cobbles and boulders. They are normally towed over the ocean bottom or up steep slopes for a certain distance, and they catch up whatever material lies in their path. They may consist of a simple large diameter pipe, or a rectangular metal frame with a chain or mesh bag attached. Dredges are generally of simple design and low cost since they are frequently caught up on the rough bottom and may be lost (they are attached to the wire by a safety release mechanism which breaks when the tension on the wire reaches a predetermined level). The primitive nature and inadequacy of geological sampling techniques can be better realized if one imagines a continental geologist trying to sample the Rocky Mountains by flying over them in a plane at a height of 2 or 3 kilometers, above the clouds, dragging a bucket on the end of a wire!

4. Traps

These are sampling devices used to catch suspended matter in the water. Varieties consist of stationary net-type traps suspended above the bottom; water samplers, which are large bottles that close at a predetermined depth to collect a sample of water and the suspended matter therein; and pumps which are first lowered to a required depth and which then pump the water through a filter that retains the desired particle size.

D. Geophysical measurements

In order to infer the geologic structure and composition of the earth's crust beneath the sea, marine geologists make a variety of geophysical measurements. They measure properties of the earth's natural force field, gravity, and magnetism; the rate of flow of heat outwards from the earth's surface; and the seismic properties of the earth's surface.

1. Gravity

Measurements of the variation in the acceleration due to gravity can be made at sea on board ship. The variations can be interpreted in terms of the distribution of mass beneath the ship. Providing that these measurements are corrected for the depth of water then the variations in the corrected gravity anomalies are caused by variation in the density of the sea floor or anomalous masses beneath the floor. Measurement of the acceleration can be done using the period of a pendulum or the pull of gravity against the pull of a spring of calibrated characteristics. The problems of work at sea are those of compensating for the acceleration of the platform on which the measuring device is mounted - acceleration caused principally by ocean waves. The tolerances of gimbal-mounted, multiple pendulum systems are small and measurements are usually limited to submerged vessels. Gravity meters using a dampened measuring spring are commonly used nowadays, and continuous measurements can be made whilst the ship is underway allowing large scale surveys and maps of gravity anomalies to be drawn.

2. Geomagnetism

A very simple, but effective method of geophysical investigation can be done by towing a total intensity magnetometer over the earth's surface by airplane or ship. In principle the device consists of a coil wound around a bottle filled with liquid (water or a hydrocarbon) composed, in part, of hydrogen molecules. A strong direct current is passed through the coil for a few seconds causing the axes of the hydrogen protons in the liquid to align along the axis of the coil. After the current is shut off, the protons realign with the earth's magnetic field. The coild is connected to an amplifier and the frequency of a very weak signal is measured. The signal is produced by the presession of aligned protons (which have both magnetic and angular momentum) about the total magnetic field vector of the earth. Variations in the frequency of this signal, after the earth's magnetic field effect is removed, reflect the magnetic effects of local geologis features.

Generally, over the sea floor, the magnetic measurements are most strongly affected by the magnetic properties of the igneous rocks even though these rocks may be buried under sediments. The important magnetic mineral in these rocks is magnetite, and changes in the magnetometer measurements could reflect changes in the magnetite content of the rocks. The magnetic properties of the rocks also depend on the direction of the earth's magnetic field, its polarity, at the time the rock cooled. Marked changes in the direction of the magnetic measurements thus may indicate rocks which cooled at different times at different times in the earth's history when the polarity was reversed. The symmetry of the magnetic properties of rocks on either side of the mid-ocean ridge axes have been, in large part, responsible for the arguments in favor of sea floor spreading (see Figure 10).

3. Heat flow

Heat flow at the earth's surface beneath the sea is measured by inserting a temperature measuring probe into the first few feet of the sea floor. Temperature differences along the length of the probe represent the temperature gradient at the earth's surface. This gradient can be expressed in terms of heat flow (calories per cm^2 per second) if the thermal conductivity of the material where the probe was inserted is known. The thermal conductivity can be measured from a core sample taken at the same position on the sea floor.

Heat flow measurements to date indicate values at the ocean floor similar to those on the surface of continents. This is somewhat surprising since most of the heat measured in continents is believed to come from the disintegration of radioactive elements in continental rocks. The heat reaching the ocean floor is believed, therefore, to come from beneath the crust and lends support to the idea of convection cells in the mantle (see Figure 10).

4. Seismic studies

Knowledge of the structure and thickness of the earth's crust beneath the sea have come from seismic techniques based on the measurement of the propagation of seismic energy. The beismic or sound energy is generated from some source such as an explosion of T.N.T., the discharge of a powerful electric arc, or a disc-piston trnasducer (which relies on the compression and sudden release of a gas) and is received by sensitive hydrophones at varying distances from the source and recorded. The time of arrival of any given sound wave is taken from the recording or oscillogram and the path from source to detector can be ascertained. From the path or distance travelled and the time taken, the speed of propagation can be computed. By recording either a line of shots at a fixed receiving position or single travel time and distance can be established. From this relationship the number and thickness of sub-surface strata can be determined and the speed of sound in each can be estimated.

The theory of seismic measurement and the details of the equipment used are dealt with in detail in some of the oceanographic texts in the reference list (see pages 42-46). The interpretation of oscillograms requires some experience and depends on identifying the type of wave being received - reflected or refracted.

a. Reflected waves

If the interface between strata is a good reflector then the thickness of the strata can be measured from the time required for a pulse of sonic energy to travel through the layer and back by reflection. Knowing the speed of sound in a particular layer allows inferences to be made about the type of material constituting the layer. Standard echo sounders measure the water depth in this way - relying on the reflected wave from the sea-water-sea-floor interface. By varying the frequency of the sound source, penetration of the bottom can be made and reflections from sub-strata received. In general, high frequency gives good resolution but little penetration. Low frequency sound sources, such as those from T.N.T. explosions, may penetrate a few thousand meters and reflect from major strata changes.

b. Refracted waves

Sound waves can also be refracted at an interface between media in which the sound wave has different velocities. Seismic refraction can, under certain conditions, not only give information concerning the velocity of sound in a given layer, but also the angle of dip of the interface.

5. Other techniques

Other techniques employed by the geologist include underwater photography (cameras can be lowered to the bottom and activated on command or by contact with the bottom). Some cameras are mounted on sampling equipment such as corers in order to give information on the orientation of the core. Television cameras also offer an opportunity of looking directly at the bottom. The scuba-diving marine geologist is generally restricted to a water depth of 100 to 200 meters. Deep-diving submersibles are now available that can extend the range of direct observation to depths up to 2,000 meters. Some of the submersibles are equipped with sampling devices, including grabs, core tubes, and drills. These are all important new developments since they allow, for the first tiem, (a) direct contact with the sea floor rather than indirect, (b) selective sampling of rock outcrops or sediments, and (c) measurements of the strike and dip of strata.

Recently, in large part due to the technological progress of the oil companies in offshore drilling, the geologist has extended his sampling technique of coring by using large drills mounted on special vessels. These drills are capable of drilling hundreds of feet below the sea floor even in depths of water exceeding 4,000 meters. The results of such drilling are only now becoming available and they promise to markedly increase our knowledge of the geology of the sea floor.

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Chapter 3: Pp 47-62 not filmed at author's request.

4. PHYSICAL PROPERTIES OF SEA WATER

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Woods Hole Oceanographic Institution

Water is probably the most familiar substance on earth, but it is also very unusual in many ways. Ocean water, which is about 30 times as abundant as all other forms of water combined, has some peculiarities of its own. We will talk a little bit about the general characteristics of water, then will go on to a detailed discussion of the properties of sea water, principally temperature and salinity, and their distribution in the oceans.

One unusual fact about water is that it is the only substance that is naturally present on earth simultaneously and abundantly in all three states: gas, liquid, and solid. On a winter day you can skate upon solid water which is supported from underneath by liquid water, while in the atmosphere there is invisible water vapor. We are all so accustomed to this that we rarely stop to realize that it is unusual.

Another peculiarity of water -- and a useful one -- is that ice floats; that is to say, water in the solid state is less dense that liquid water. Furthermore, pure water reaches its maximum density several degrees above freezing point, unlike most substances which continue to contract and become denser as they are cooled. Pure water contracts as it is cooled until it reaches 4°C, after which it expands slowly until 0°, when it suddenly expands rapidly upon crystallization into ice. This characteristic of water helps to increase the productivity of fresh water lakes and ponds by producing the so-called "double turnover" each year so that the lake is deeply stirred and the nutrient-rich bottom water is brought to the surface where it can be utilized for plant growth. In the summer the surface water, warmed by the sun, is less dense than the colder water below and therefore stays at the surface. During the fall and early winter it is cooled from above, becomes denser and sinks, replacing the deeper water to the upper layers. When the surface water is cooled to 4° it has reached maximum density; if it is cooled further it will become less dense and no further mixing will take place. This means that even in relatively shallow ponds the bottom water is not likely to cool much below 4° even in a winter cold enough to form ice several inches thick at the surface: a fact of some importance to animals living in the bottom mud. When spring comes, with warmer weather, the surface water will become denser as it is warmed and will sink through the less dense water below, once again stirring up the bottom waters to feed the spring bloom of planktonic plants.

Sea water, which contains dissolved salts, does not behave like fresh water in this respect, but continues to increase in density as it is cooled, right down to the freezing point. The freezing point of sea water, incidentally, is several degrees below that of fresh water, because of the presence of dissolved salts.

Some other unusual but useful properties of water are its high specific heat, or capacity to absorb heat without becoming much hotter itself (which explains why seashore temperatures are moderate); its high latent heat of fusion and evaporation (which explain why water keeps cool in a Lister bag on a hot day or why a pan of water in a greenhouse can keep the plants from freezing on a cold night); and its high surface tension.

Water is also a universal solvent: every element known to man has been found dissolved in sea water. Yet it is an inert solvent in that it is not changed chemically by the substances it dissolves. It remains H_2O. All of these unusual characteristics of water result from its peculiar molecular structure, which will not be discussed here, but which is fully covered in Water, a Mirror of Science, by Davis and Day.

In the ocean the characteristics of sea water which concern us most are temperature and salinity. They are important for a number of reasons. In the first place, except at the sea surface they are conservative properties; that is, there is no way to add heat or salt to sea water except at the surface. For this reason both temperature and salt are useful as tags for identifying and tracing water masses. Furthermore, temperature

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Note: Except for Fig. 10, these figures were taken from "Elements of Physical Oceanography ," by H. J. McLellan, Pergamon Press 1965.

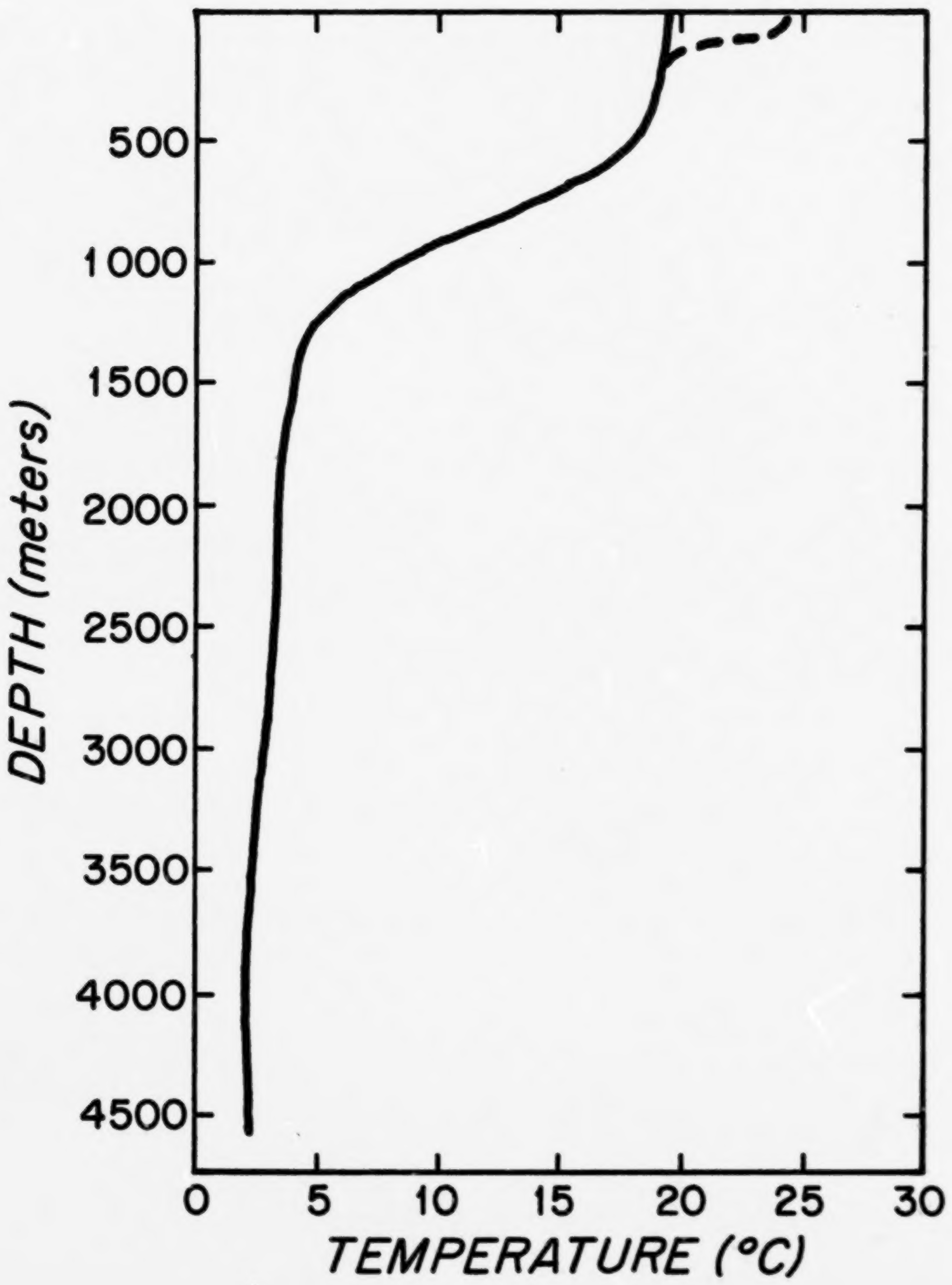

Figure 1. Typical trace of temperature vs. depth in the Sargasso Sea in the winter. Dotted line shows seasonal thermocline.

and salinity are the most important variables affecting the density of sea water, and it is the distribution of density in the ocean that determines the principal features of the oceanic circulation. Finally, temperature and salinity are important to the biologist because they determine the kinds of plants and animals that can live in a given body of water.

Fortunately it is possible to measure both temperature and salinity quite accurately. Let us consider them separately.

The range of temperature in the ocean is about -2°C to 32°C, roughly comparable to the seasonal variation of temperature in the central United States. However, the great bulk of the water in the ocean is much more uniform in temperature: 75 per cent of it lies in the range 0°C to 6°C and one half of it is between 1.3°C and 3.8°C. The reason for this is that the deep water of all the oceans has its sources at high latitudes, and is therefore quite cold even at the equator. Figure 1 is a typical mid-latitude trace of temperature versus depth, taken in the Sargasso Sea in the wintertime. There are three principal zones; 1) a warm layer near the surface where mixing by the wind and other processes has produced a nearly uniform temperature down to a depth of a few hundred meters; 2) a thermocline, or layer in which the temperature drops very rapidly with increasing depth; and 3) the deep water, where the temperature continues to decrease as the depth increases, but much more slowly than in the thermocline. In the summertime, heating from the atmosphere may add a seasonal thermocline as shown by the dotted line. The actual temperature and the depth of the thermocline will vary widely depending upon the location and the time of the year, but except in extreme high latitudes where even the surface water is cold, the general picture will be the same.

It is clear from the figure that to describe the temperature distribution in the deep water will require much more accurate techniques than are necessary in the more variegated upper layers. There are many ways to measure temperature, but for three quarters of a century the principal tool for the deep water has been the reversing thermometer

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attached to a Nansen bottle for taking water samples. Carefully calibrated and corrected, a good reversing thermometer is capable of accuracy to a few thousandths of a degree.

The trouble with using an ordinary thermometer at any depth is that its reading will change as it moves through the changing temperatures of the water, so that even if it is pulled up rapidly and read right away it will give a false temperature. Early oceanographers tried to get around this problem by encasing the thermometer bulb in a ball of wax to insulate it, but the results were not satisfactory. The reversing thermometer (see Figure 2) solves the problem in this way. The thermometer is built with a narrow constriction in the glass column just above the bulb. The open Nansen bottle is attached to the hydrographic wire with the thermometer in position A (note that the temperature scale is upside down), and the instrument is lowered to the desired depth. A messenger, or small weight, is dropped down the wire to release the upper end of the Nansen bottle, so that the bottle turns over and the valves are closed, trapping a quantity of water for later analysis. When the Nansen bottle is upended, so is the thermometer. The mercury column breaks off at the constriction and flows into the other end of the thermometer, where it remains while the thermometer is being hauled back aboard. When the instrument is on board, the temperature at the point of reversal can be read, on the now right-side-up scale. A small auxiliary thermometer alongside the main one is used to correct for any change due to the room temperature where the thermometer is read.

Reversing thermometers are also used to determine the actual depth at which the observation was made. (The amount of wire over the side is not reliable because it may not hang straight down.)

The depth of the ocean itself is generally determined by echo sounding, which we will say more about later, but the depth of an instrument is usually found by measuring pressure. The pressure at a point in the ocean is simply the weight of water, per square centimeter, above that point, and as the density of sea water is almost a constant, pressure is an excellent measure of depth. In fact, when metric units are used, it works out that the

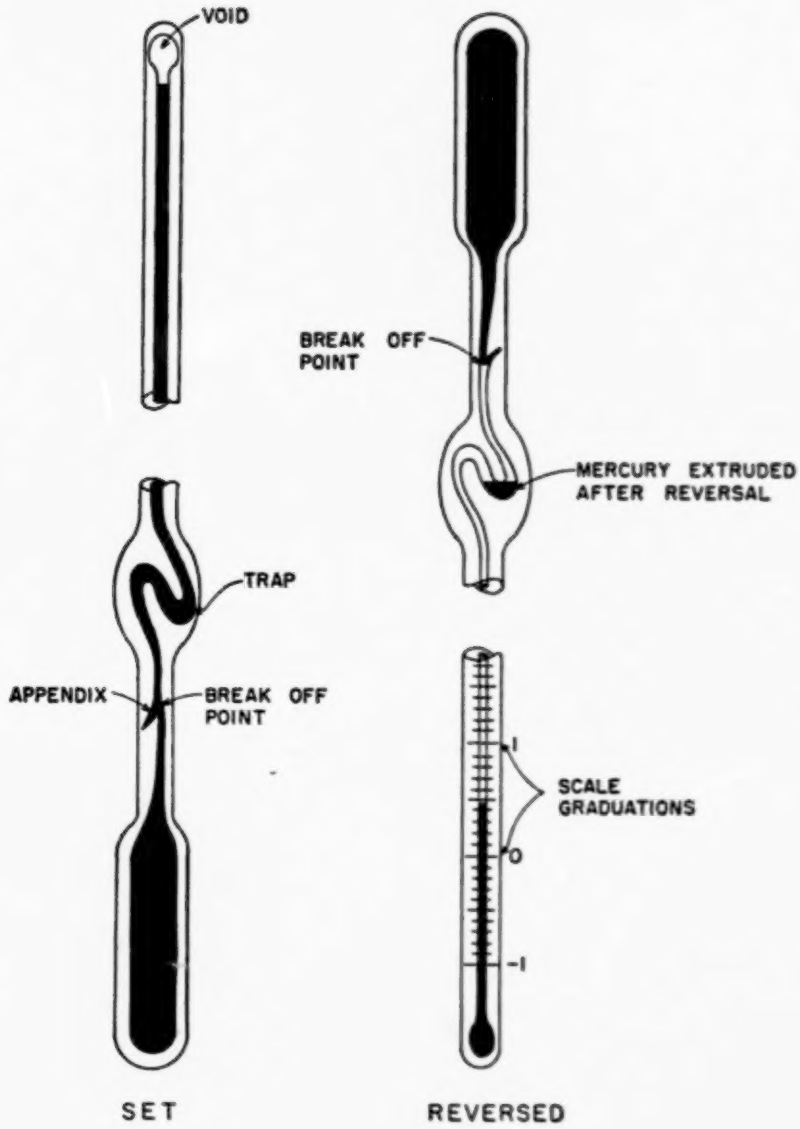
VOID
BREAK OFF POINT
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Figure 2. Details of reversing thermometer.

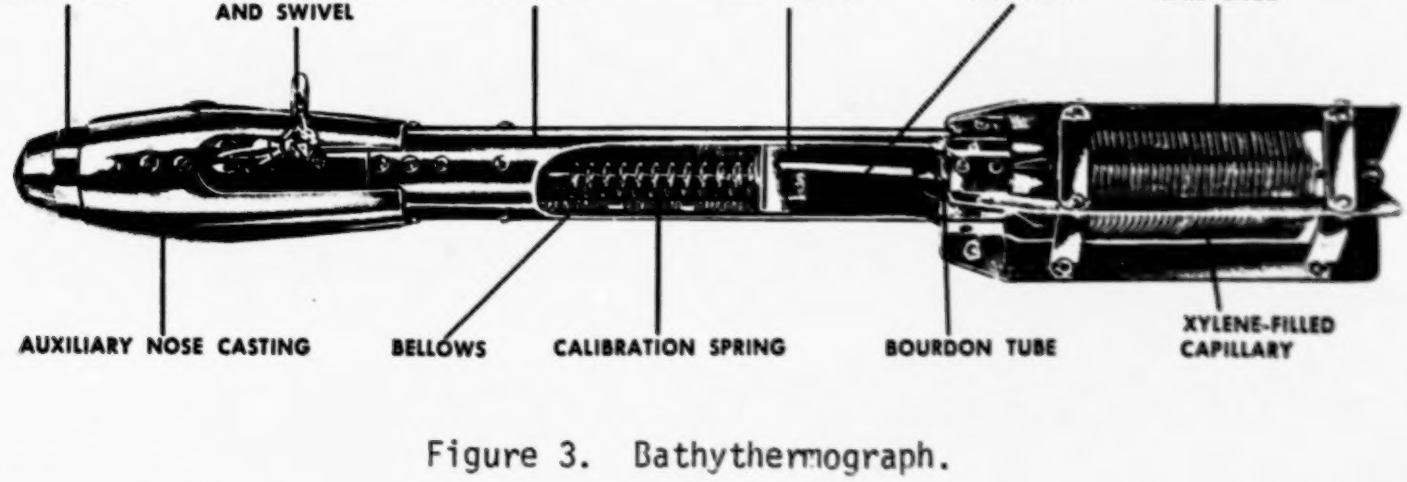
NOSE PIECE
CABLE SHACKLE AND SWIVEL
BODY TUBE
SLIDE HOLDER
PEN ARM
TAIL CAGE
AUXILIARY NOSE CASTING
BELLOWS
CALIBRATION SPRING
BOURDON TUBE
XYLENE-FILLED CAPILLARY

Figure 3. Bathythermograph.

pressure in the ocean increases one atmosphere for every 10 meters of depth, so the pressure in decibars (one decibar equals 1/10 of an atmosphere) is equal to the depth in meters.

To measure depth by reversing thermometers two thermometers are attached to a Nansen bottle. One thermometer is encased in a heavy glass tube and squirts the mercury up so that the temperature reading is higher than it should be. The temperature difference between the two thermometers is thus a measure of the pressure at the point of reversal, and the pressure is a measure of depth. The difference in temperature is generally 1 degree for every 100 meters in depth, so with a good instrument, carefully calibrated, the depth can be determined to within 5 meters per 1000 meter depth, or less than 1/2%.

Another effect of pressure should be mentioned here. It is a well known thermodynamic principle that the temperature of a substance will increase if it is subjected to pressure even if no heat is added. This effect, known as adiabatic warming, is of considerable importance to meteorologists and is a principal reason why the atmosphere is much colder at high altitudes than it is near the earth's surface where the pressure is higher. More familiar, perhaps, is the rush of cold air from a bicycle tire when you depress the valve, an example of the phenomenon in reverse. Adiabatic warming occurs in the sea: sea water at depth is under pressure and so it is warmer than it would be at the surface. The effect is small--about .01° for 100 meters depth--and can generally be neglected in the upper layers, but it noticeable in the deeper waters. Temperatures in deep water are often adjusted to remove this pressure effect. When such an adjustment is made the resulting temperature is called "potential temperature" and represents the temperature a given bit of water would have if it were brought to atmospheric pressure without adding or taking away heat.

Getting back to temperature measurment, we have seen how the combination of reversing thermometers and Nansen bottle can provide a water sample, the depth at which the sample was taken, and the temperature at that depth at the time of sampling. Usually twenty to thirty such observations are made at different depths at an oceanographic station; dozens or even hundreds of stations may be taken on a single oceanographic cruise, so that the distribution of temperature throughout a given portion of the ocean can be reliably plotted. To look at gross features of the temperature structure, stations 30 to 60 miles apart are usually sufficient, but for a detailed picture, in areas such as the Gulf Stream, it is not unusual to reduce the spacing to five to ten miles.

One difficulty with the standard oceanographic station is that it takes time — up to four hours for a deep station — and the ship must be stopped while the wire is over the side. There is no real substitute for this method of investigating the deep water, but for the upper layers of the ocean the temperature structure is often determined by a less accurate but more convenient instrument called a bathythermograph, or BT. The BT is a sort of diving thermometer that can be used while a ship is underway. There are two kinds of BT in use today. The older model (see Figure 3) is a mechnaical device which records temperature and depth continuously on a smoked glass slide, and can be brought back aboard and used over and over again. It is tricky and time-consuming, not very accurate, and can be used only to a depth of 250 meters even from a slowly-moving ship. A more recent development is the expendable BT, a bomb-shaped device which is connected to the ship by a very fine conducting wire by which the temperature sensor is connected to a shipboard recorder. As the Bt sinks the wire is paid out like line from a spinning reel, until the maximum depth of 500 meters is reached, when the wire breaks. The temperature sensor is a thermistor, a solid state device which changes its electrical resistance as its temperature changes. The expendable BT is more accurate than the mechanical BT, it measures temperature at greater depths, and it can be used at speeds up to 30 knots.

Salinity is a little more difficult to pin down than temperature. There is no question that the most distinctive feature of sea water is its saltiness, but to describe it exactly is another matter. The average person is content to know that sea water is too salty to drink, but for anyone concerned with the marine environment it is necessary to use numbers.

For many purposes -- such as marine engineering -- it is enough to know that sea water is a salt solution of about 3.5 per cent, or as oceanographers put it, 35 parts per thousand (^{o}/oo). One per cent equals 10 parts per thousand. Actually 90 per cent of all the water in the oceans is within one part per thousand of the mean value, although the total range goes from about 8 ^{o}/oo in areas of extreme precipitation like the Baltic Sea to about 40^{o}/oo in high-evaporation basins like the Mediterranean and Red Seas.

The marine scientist needs to know salinity much more precisely, at least to two decimal places, i.e. 34.73^{o}/oo, and it is necessary to go three decimal places, i.e. 34.726^{o}/oo, to be able to discern the small but significant differences that occur in the deep water.

In the North Atlantic Ocean, salinity varies with depth much as temperature does (see Figure 4,a): There is a mixed layer of high salinity at the surface, followed by a halocline in which salinity decreases rapidly as the depth increases, and finally a deep layer in which the salinity continues to decrease, but much more slowly. The North Atlantic is not typical in this respect, however. Largely because it receives a continuous supply of very salty water from the Mediterranean through the Straits of Gibraltar, it is the saltiest of all the oceans, with a mean of 35.1^{o}/oo compared to the world mean of 34.7^{o}/oo. A more representative salinity trade is shown in Figure 4,b, from observations in the central Pacific Ocean. It shows relatively fresh surface water, increasing to a maximum salinity at about 200 meters, then decreasing to a minimum around 800 meters, and finally increasing again, much more slowly, in the deep water. In both regions you can see that high accuracy is needed to see any structure in the deep water.

To measure salinity it is necessary to know just what it is, and that introduces another complication. Salinity is not a fundamental quantity like temperature, rooted in basic scientific principles. Instead, "salinity" refers to all the dissolved material in the oceans and, as has been said earlier, every element known to man has been found in solution in the ocean. Strictly speaking, then, to measure what we call "salinity" you should analyze a water sample dozens of times, to determine the precise quantity of every element present. This would of course be terribly tedious and would require impossibly large water samples -- much bigger than the quart-and-a-half obtained with a Nansen bottle.

For nearly a century oceanographers met this problem by making use of a very convenient fact: The ocean is, generally speaking, well-mixed. On the few occasions when thorough analysis has been made, the major constituents of sea water were found to occur in nearly the same proportion to each other. In other words, the differences in salinity in sea water are *not* caused by changing the relative abundance of any of the dissolved materials, but by adding or removing H_2O. This is reasonable, of course, because the major changes in salinity occur because of rain and snow, which add fresh water, or evaporation and freezing, which remove it.

What this means for the oceanographer is that once the relative proportions of the dissolved substances has been determined, it is only necessary to measure one of them in order to know them all. And until very recently the usual method of determining salinity was to run an analysis for chlorine, one of the two most abundant dissolved elements in sea water, and then simply multiply the chlorinity by a fixed fadtor to get the salinity. (The other very abundant element in sea water of course is sodium. Together sodium and chlorine form 85 per cent of the total dissolved matter in the ocean and account for its familiar "table salt" taste.)

The analysis for chlorine, a routine chemical titration, is relatively simple to perform and is accurate to about .02^{o}/oo in salinity, which is adequate for the upper layers of the ocean. However, it involves very careful measurement of liquids, which is difficult to achieve in a shipboard laboratory in rough weather, and it is not nearly accurate enough for deep water work. In recent years a new technique has been developed which is both easier to do at sea and much more accurate. Instead of chemical analysis, an electronic determination is made of the electrical conductivity of a sea water sample. Electrical conductivity actually depends upon both the temperature and the total dissolved material -- which is, of course, what is means by salinity. The samples are kept at a constant temperature

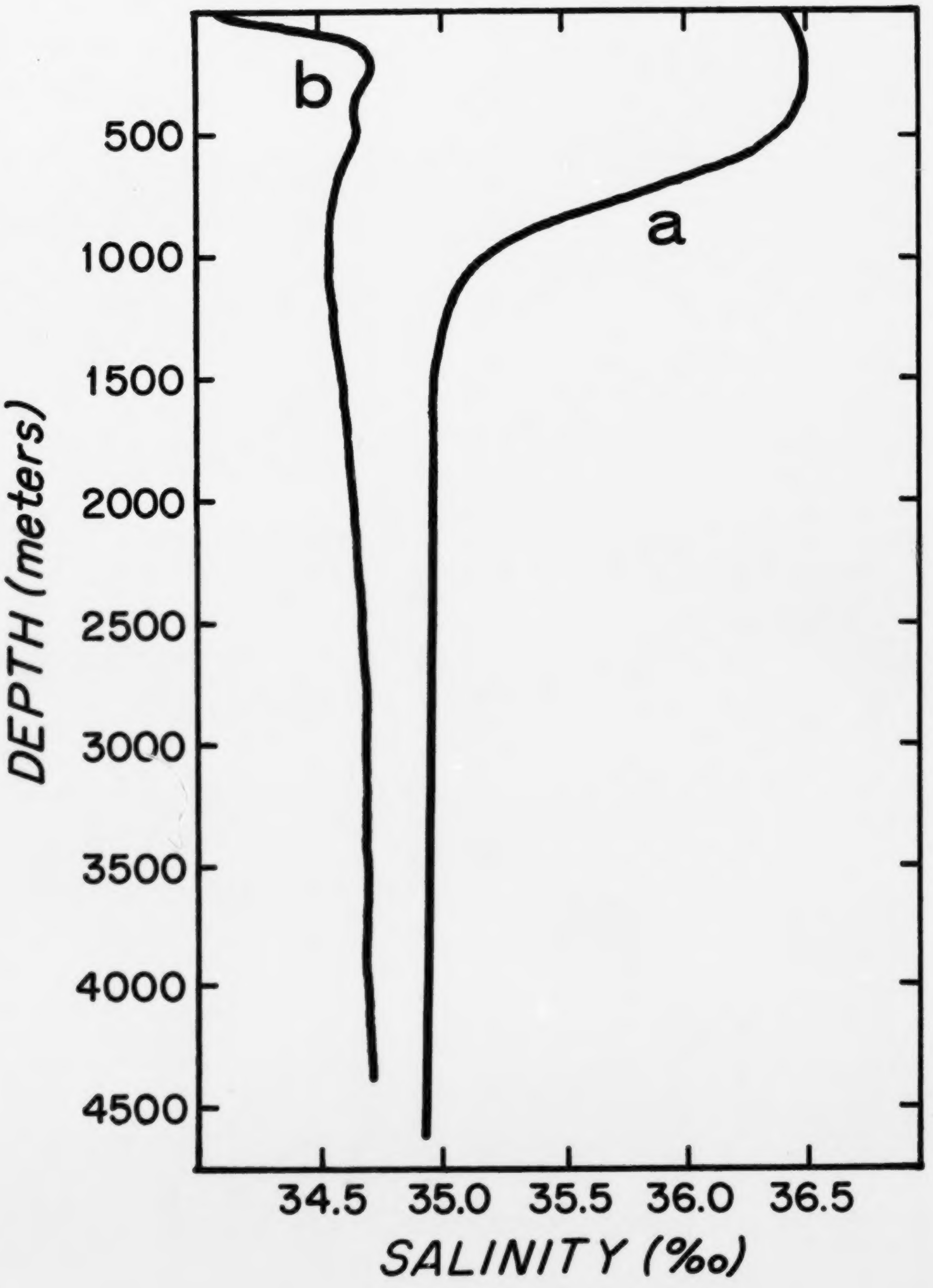

Figure 4. Typical traces of salinity versus depth: a) in the Sargasso Sea; b) in the Central Pacific.

so that differences in conductivity will represent differences in salinity only. With this method salinities good to $.003^{o}$/oo are obtained.

It should be mentioned that because salinity is not a fundamental quantity there is no absolute standard against which it can be measured. Instead, for both titration and conductivity measurement, the unknown samples are compared with a very carefully prepared standard, which comes from Denmark and is known as "Copenhagen water."

Instruments which can be lowered over the side to measure conductivity and temperature (and therefore salinity) continuously as a function of depth have been designed and tested. They have the great advantage that they show small scale variations that are missed by the spacing of samples in a Nansen bottle cast, but they have not begun to approach the reliability and accuracy of the classical technique, and the standard method of obtaining temperature and salinity information about the ocean is still the lowering, at specific stations, of Nansen bottles with reversing thermometers attached.

Such an oceanographic station results in a series of observations at different depths at a fixed point in the ocean (or nearly fixed -- a ship may drift as much as a mile or two while "on station"). To get a meaningful picture of the distribution of temperature or salinity over a large area, an oceanographer usually plots the data on either horizontal charts or in vertical sections; that is, he slices the ocean either like a stack of pancakes or like a loaf of bread. The plotting is usually done by drawing lines connecting points of equal value. On a temperature chart such lines are called isotherms (one line might show the depth of the 10^{o} isotherm, for example); on a salinity chart they are called isohalines.

Horizontal charts are usually used for the sea surface and the upper layers of the ocean, where differences in temperature and salinity tend to be related to latitude because of atmospheric influences. Thus in Figure 5, showing surface temperature in the northern winter, we see the warm water along the equator, cooling both north and south to temperatures near the freezing point at high latitudes. The only real break in the pattern occurs along the western sides of the North Atlantic and North

Pacific oceans, where the Gulf Stream and Kuroshio current carry warm water well to the north. The surface salinity distribution (see Figure 6) shows salinity peaks at the "desert" latitudes of 25^{o}-30^{o}, both north and south, with lower values both in the "rain forest" belt of the tropics and in higher latitudes where evaporation is lower.

To look at the deep water, vertical sections are used, generally following the track of a researdh vessel as it crosses an ocean basin or some smaller-scale feature. In some cases, as in the figures shown here, the section is a composite of stations made on several differenct cruises, put together to give a north-south picture of an entire ocean from the Antarctic to the Arctic.

It is important to remember in any vertical display such as these that there is tremendous exaggeration: the vertical scale may be 500 or 1000 times the horizontal scale. In these figures the exaggeration is about 1000 times: the ocean appears about three times as long as it is deep whereas actually it is about three thousand times as long. To do it with the same scale in both dimensions would reduce the depth to about the thickness of a pencil line so that no detail could be seen. The shape of the bottom is exaggerated to the same degree, of course; those sharp peaks and deep trenches in the section are actually pretty flat.

Figure 7, a and b, shows temperature and salinity in the Atlantic Ocean. North is at the right. In the temperature section, the thermocline is evident in the closely spaced isotherms near the surface, while the wide spacing in the depths indicates a region of little variation. The coldest bottom water, of Antarctic origin, can be seen at the south, while another cold water mass, originating in the Norwegian Sea, moves southward. In the salinity section the effect of the Mediterranean outflow can be recognized in the deep penetration of water of more than $35^{o}/oo$ and in the tongue of deep salty water which reaches to mid-latitudes south of the equator. The Pacific Ocean sections, Figure 8, a and b, on the other hand, are considerably simpler, because the Pacific has no northern source comparable to either the Mediterranean or the Norwegian Sea.

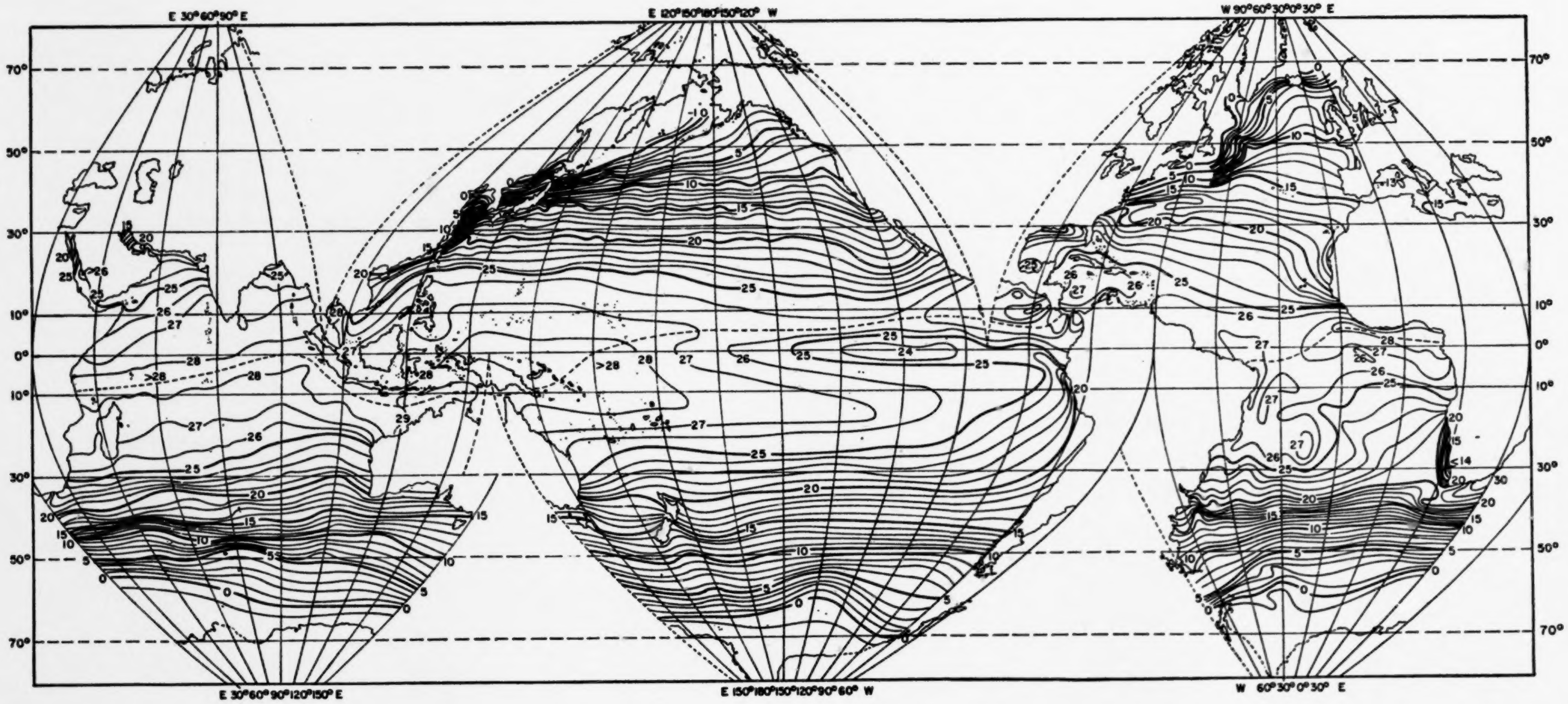
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Figure 5. Sea surface temperature of the world oceans in February.

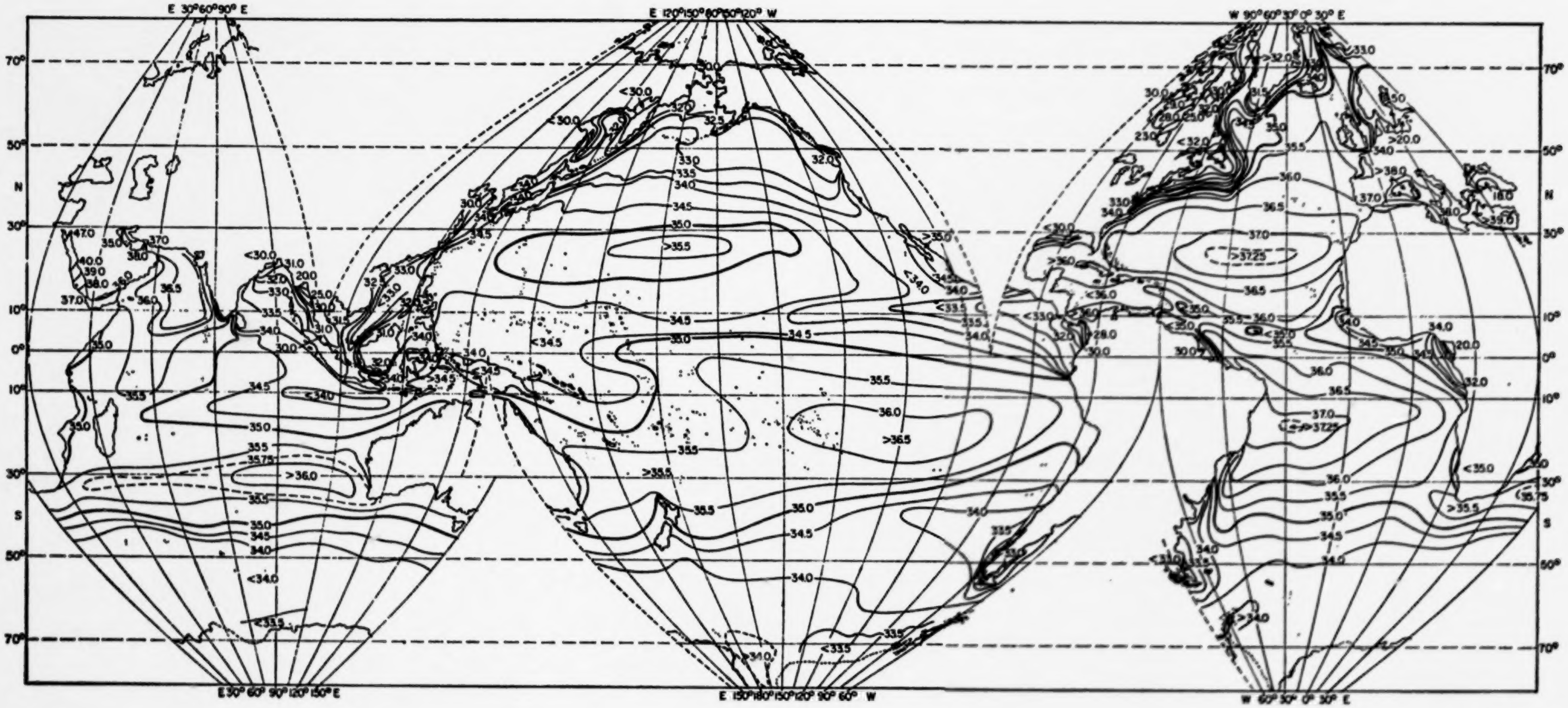
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Figure 6. Average sea surface salinity of the world oceans.

The foregoing figures show how the distribution of temperature and salinity can be used to suggest large-scale movements of water. They can also be plotted against each other in what is known as a T/S diagram. In a T/S diagram a point is plotted on a graph for each observation of temperature and salinity. Lines connecting those points result in a characteristic T/S curve for a given oceanographic station. It has been found that water masses in different parts of the ocean have distinctive T/S curves which can be used to identify them as in Figure 9.

A very important use of temperature and salinity is to determine density. As has been mentioned earlier, warm water is less dense than cold water because water shrinks on cooling. Similarly, salty water is more dense than fresh water because it contains more dissolved matter in a given volume. So cold, salty water will tend to sink and fresh, warmer water will tend to rise. Neither effect is very great, and for many purposes the density of sea water can be considered a constant, but in the absence of other forces, small density differences can be of great importance in the oceanic circulation.

Density is usually expressed in grams per cubic centimeter so that it has the same numerical value as specific gravity. The specific gravity of pure water at $0^{\circ}C$ is 1.00000. The specific gravity of sea water at $4^{\circ}C$ and $35^{\circ}/oo$ salinity is 1.02781; reducing the salinity to $20^{\circ}/oo$ would lower the figure to 1.01593, raising the temperature to $30^{\circ}C$ would lower it to 1.02175. Throughout most of the ocean the range is between 1.025 and 1.028.

Because of this small range oceanographers use a short-hand expression for density. They write

$$\sigma_T \text{ (sigma-t)} = (\rho_{STO} - 1) \times 1000$$

where ρ_{STO} is the density at the given salinity and temperature and at depth = 0. Using this relationship water at 4° and $35^{\circ}/oo$ salinity would have a sigma-t equal to

$$(1.02781 - 1) \times 1000 = .02781 \times 1000 = 27.81$$

Density in the ocean is usually figured to three decimal places in sigma-t. Tables have been prepared so that sigma-t can be quickly calculated for any combination of temperature and salinity in the ocean, and the densities of different water samples can be compared. The relationship between temperature, salinity and sigma-t is shown in Figure 10.

Notice that sigma-t refers to a water sample at 0 meters depth, that is, at the sea surface. The reason for this is that there is a third important factor which determines the density of sea water -- a factor we have omitted so far -- and that is the depth. Water is generally considered incompressable but it can, in fact, be compressed. Here again the effect is slight -- density increases by only about .00005 gms/cm^3 for every 100 meters of depth -- but given the great depth of the ocean and the equally small effects of temperature and salinity, it can seem significant. For example, if water were completely incompressible, sea level would be about 300 feet higher than it is now, Long Island and Cape Cod would be deeply submerged and only a few skyscrapers would protrude through the sea surface at the great seaport cities like New York and Tokyo.

For most oceanographic purposes this pressure effect is an inconvenience, Its effect is the same at the same depth all over the ocean, so it has no influence on the relative densities of two bodies of water at the same depth. Oceanographers, who are principally interested in those relative densities, prefer to ignore the depth effect and that is why sigma-t is referred to the sea surface. The situation is shown in Figure 11. At left, a central Pacific station is compared with a North Atlantic station using sigma-t. At right the same stations are compared on a different scale with the pressure effect included: the differences between the two are effectively wiped out in the latter.

One other important physical characteristic of sea water which depends upon temperature, salinity, and pressure is the speed of sound. Sound is particularly important to an oceanographer because it is the only form of energy which can be transmitted easily through sea water and is therefore used extensively in oceanographic instruments. The speed of sound in sea water is approximately 1500 meters/sec (about five times the speed of sound

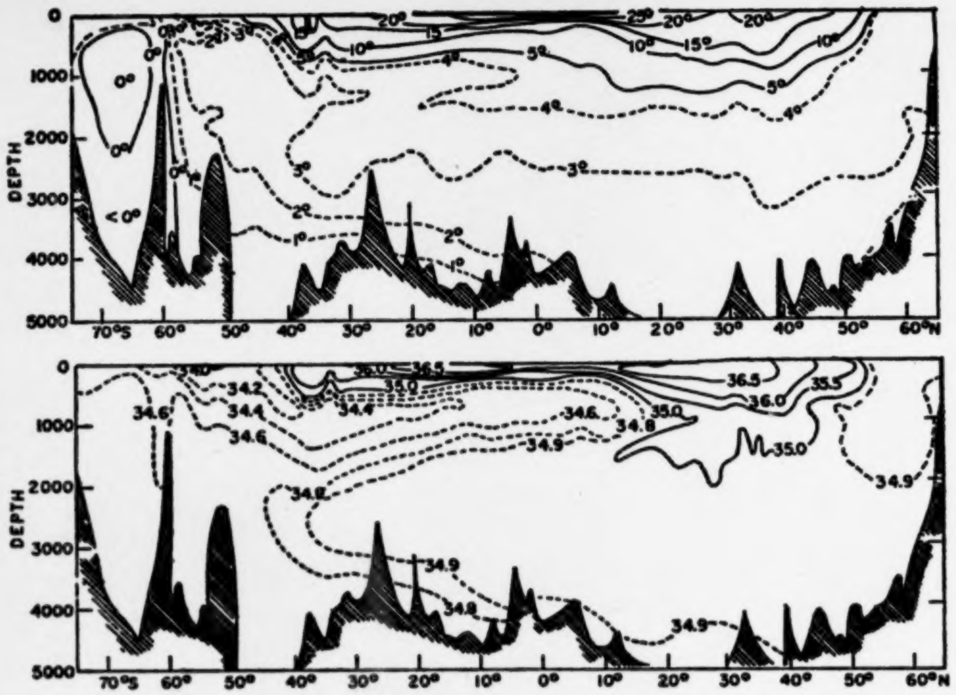

Figure 7. a) Temperature distribution in the Atlantic Ocean.
b) Salinity distribution in the Atlantic Ocean.

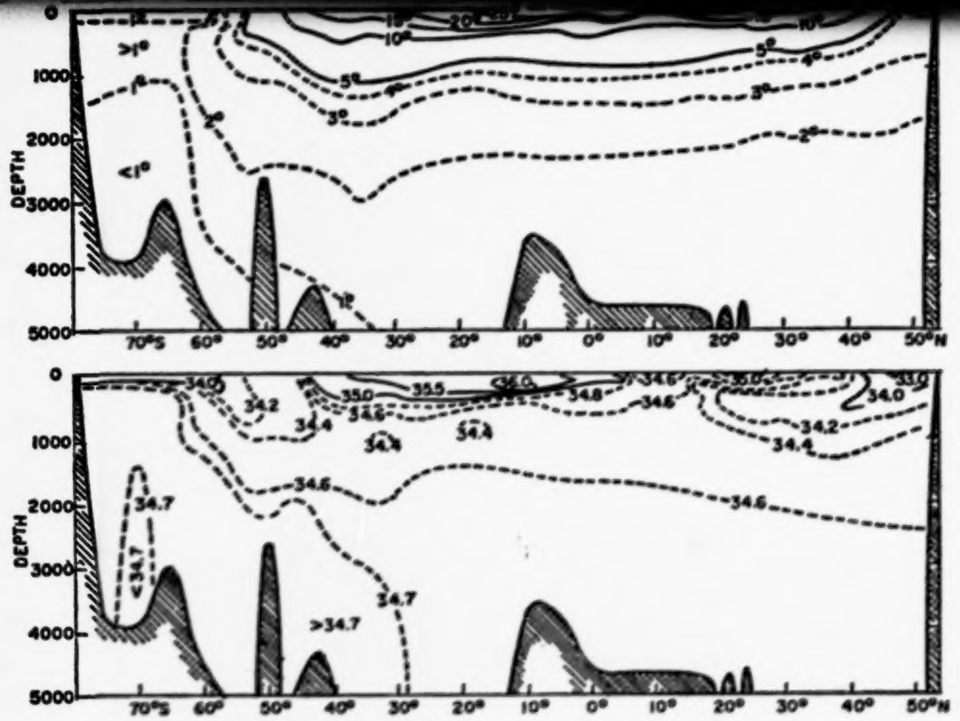

Figure 8. a) Temperature distribution in the Pacific Ocean.
b) Salinity distribution in the Pacific Ocean.

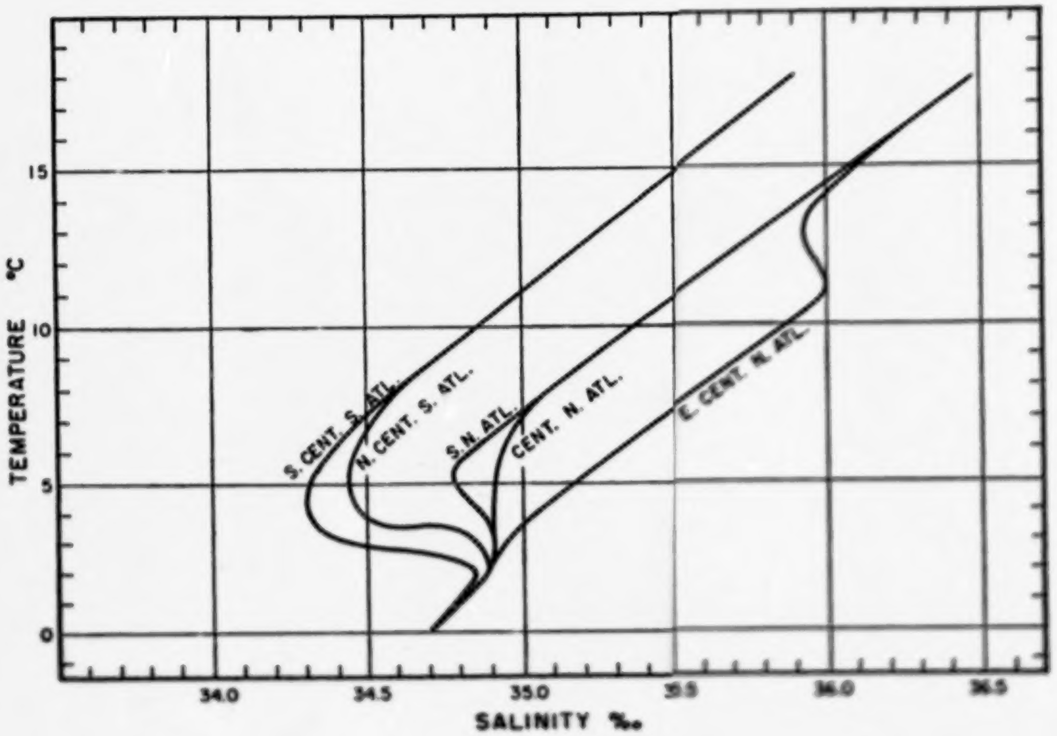

Figure 9. Some T-S curves for Atlantic Ocean water masses.

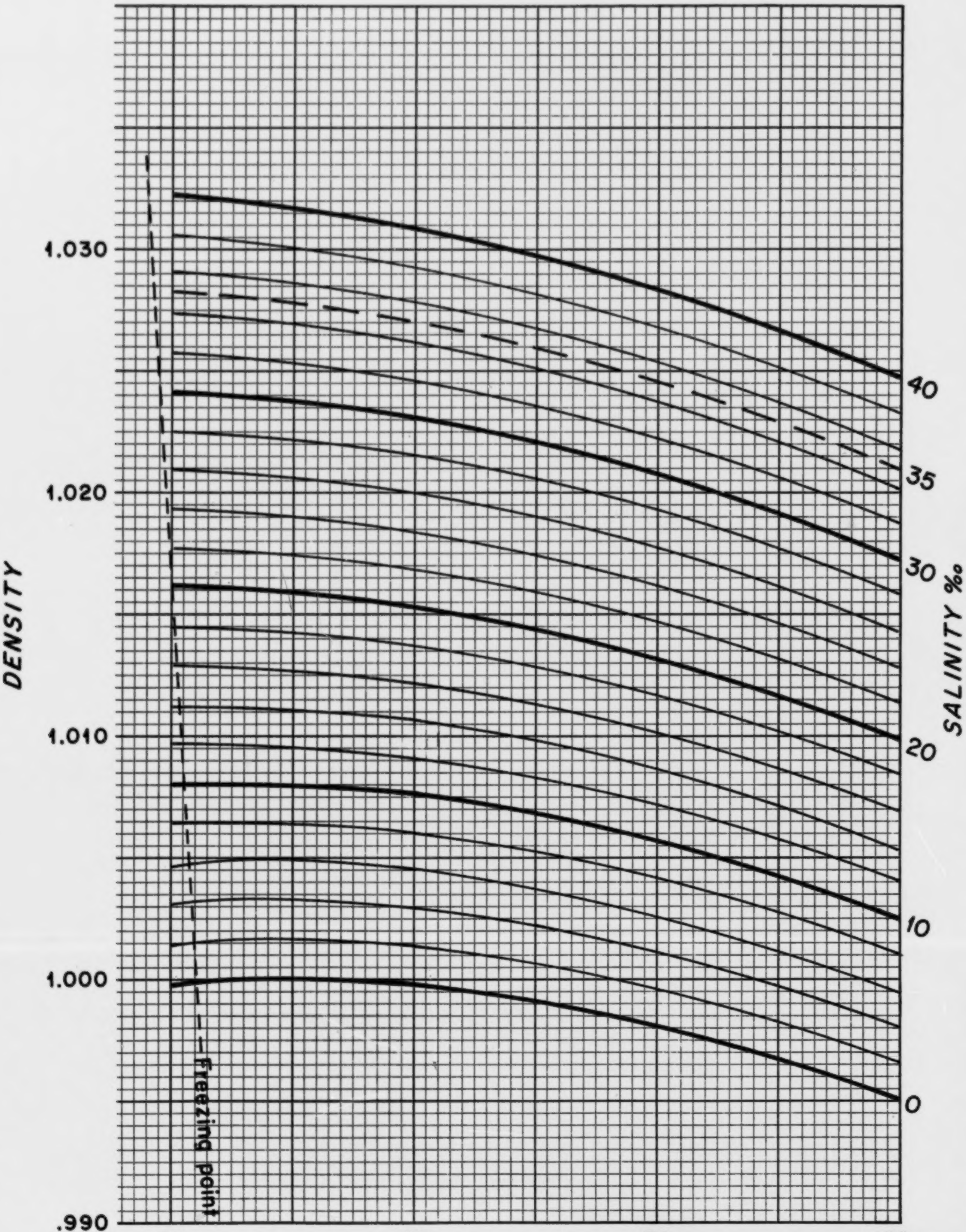

Figure 10. Graph showing the relationship among temperature, density and salinity. (Woods Hole Oceanographic Institution.)

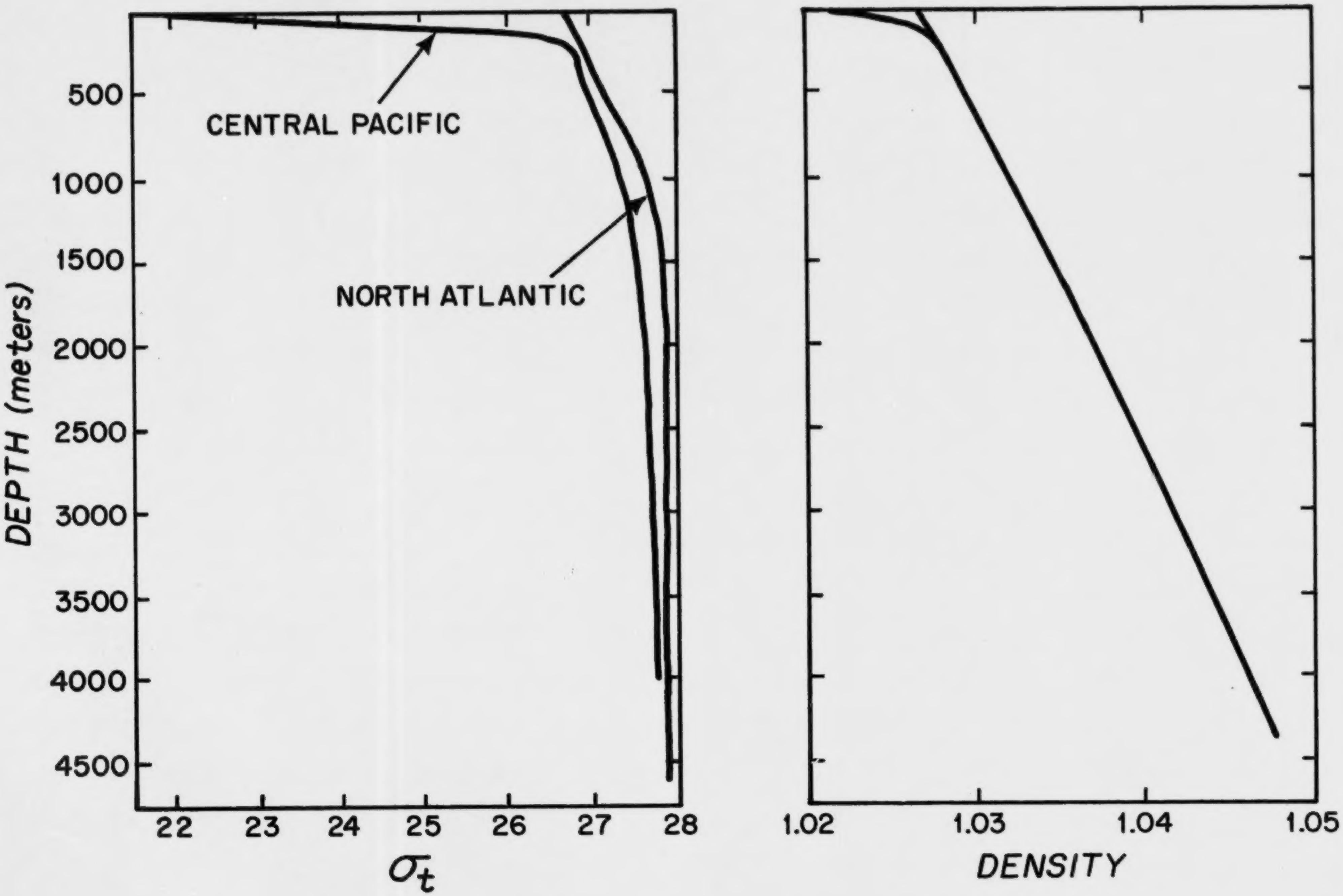

Figure 11. Comparison of typical North Atlantic and Central Pacific stations: left, sigma-t vs. depth; right, density vs. depth. Note difference in horizontal scales.

in air). Increasing temperature results in an increase of sound speed of about 3 m?sec per degree centigrade; increasing pressure increases the speed of sound by about 2 m/sec per 100 meters depth; and an increase in salinity has an even smaller effect, increasing the speed of sound by only 1.3 m/sec for each part per thousand. In the surface layers the temperature effect is the most pronounced and the speed of sound usually decrease down to the depth of the thermocline. Below that depth the temperature change is less pronounced and the pressure effect takes over, so that the speed increases toward the bottom. Sound waves can be bent by these changes in velocity, a fact of considerable importance in submarine warfare in which both the hunter and hunted rely almost exclusively on sound. Changes of sound speed are also important in precision echo sounding which measures the depth of the ocean by the time it takes a sound pulse to travel to the bottom and back to the ship. Tables giving the necessary correction to apply in different parts of the ocean are a standard part of any oceanographer's seagoing equipment.

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5. WAVES AND TIDES

by Andrew Vastano
Texas A & M

Waves

Waves which occur in nature have many forms and we are quite familiar with some of them. It is taken for granted that sound waves exist, we can sense them easily, and ocean waves are rather uneasily sensed by some of us on board ship. There are many more wave forms besides the ones we normally experience, some of which are quite foreign. For instance, there are waves within the earth generated by earthquakes and there are extremely long waves that travel hundreds of miles per hour across the ocean. In spite of an almost endless list of waves phenomena, there are two general similarities that link all waves: (1) the transmission of energy through space and time with (2) little or no permanent disturbance of the medium.

No one doubts that ocean waves can transmit large amounts of energy. They do so quite efficiently. The damage inflicted on offshore platforms during hurricanes certainly demonstrates this ability. When we say that waves do not cause a net movement of the medium, we qualify the statement for ocean waves. As the water becomes shallow, a tendency for movement increases. However, in deep water, a small floating object experiences little movement other than an up and down motion as it rides the surface of passing waves.

A detailed examination of ocean waves requires a mathematical point of view and we shall define some basic characteristics before continuing. We consider that a wave has amplitude, wavelength, period, and phase. Let's focus attention on a single train of waves of pure form moving at constant speed in a given direction without chaning shape. The particular shape of the wave train is sinusoidal and a portion is shown in Figure 1. We say that the curve represents some property of the wave such as the elevation of the ocean surface from the datum. In this case the datum is the mean water level, an equilibrium position of the surface in the absence of wave action. The amplitude (A) of the wave is defined as the maximum vertical displacement of the wave from the horizontal datum, that is, the displacement at point (a) in the figure. If we think of the length along the datum as distance, as it would be in a photograph, the horizontal length between (a) and (b) is known as the wavelength (L). When the length along the datum represents time, as in a recording of the water level at a tide station, the time interval between (a) and (b) is called the wave period (T). Wave period and wavelength represent a constant time and distance between any two points on the wave form that are of equal phase. At points of equal phase, the elevations of the sinusoidal wave are equivalent and the wave is changing in the same manner. We can understand this by imagining the wave of Figure 1 to be moving from left to right. Now the water at points (c), (d), and (e) are at the same elevation, but experience tells us that the water is rising at (c) and (e) and dropping at (d). Thus points (c) and (e) have the same phase, or are in phase, while points (c) and (d) are out of phase. The phase of a wave relative to some arbitrary origin such as the one at (f) is often used to establish space and time relationships between different wave trains.

The natural state for ocean waves is one of some degree of confusion. This is brought about by the simultaneous superposition of many wave trains of different origins and shapes. A century ago, the Frenchman Fourier demonstrated that descriptions of the most complex wave systems can be carried out by the addition of numbers of pure sinusoidal components. Each component wave in a Fourier analysis has its basic properties suitably selected according to Fourier's mathematical method. This is a remarkable milestone in scientific research and has evolved to modern spectral analysis, a powerful computer method for decomposing waves into sinusoidal or spectral components for study. Thus, investigators find it convenient to examine ocean waves and tides according to their component frequencies. The wave

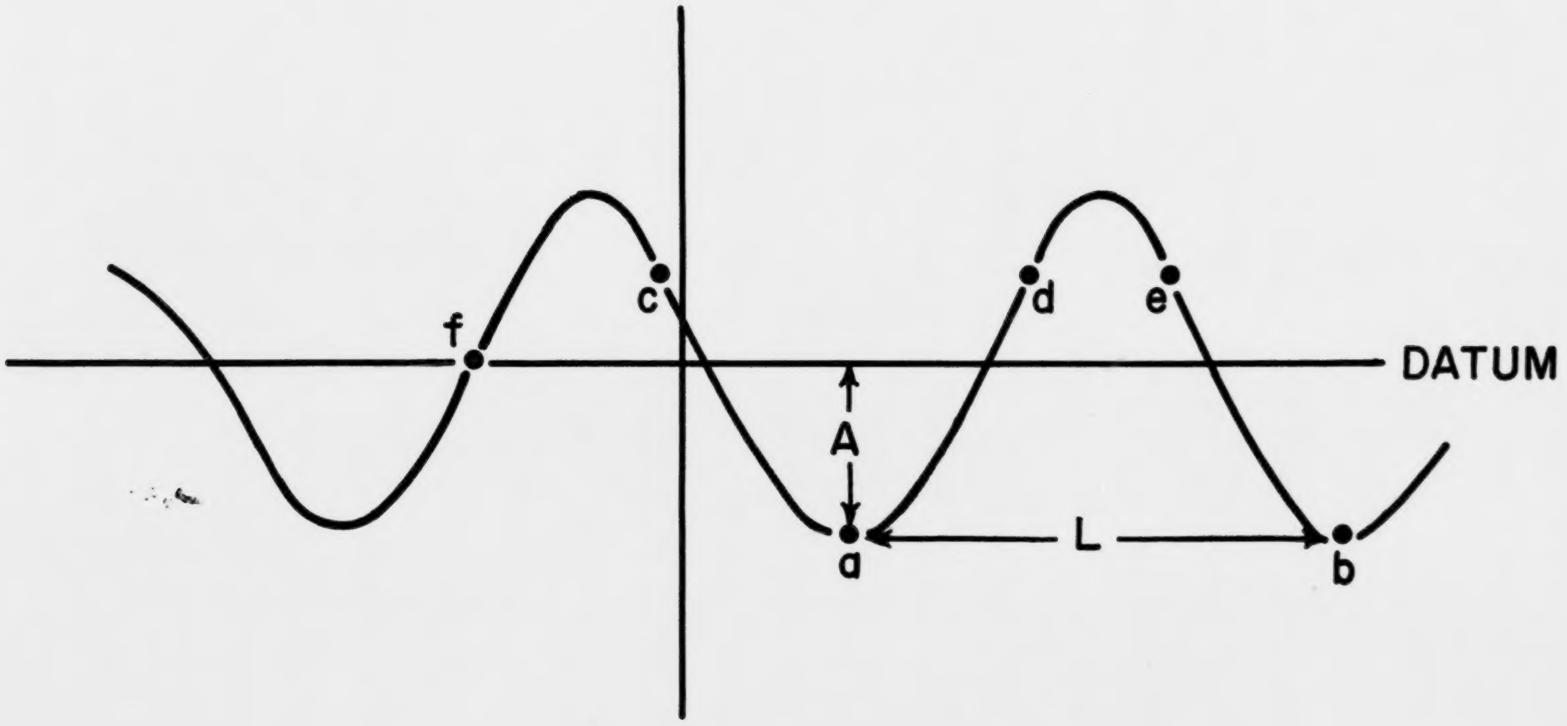
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Fig. 1. Sinusoidal wave form.

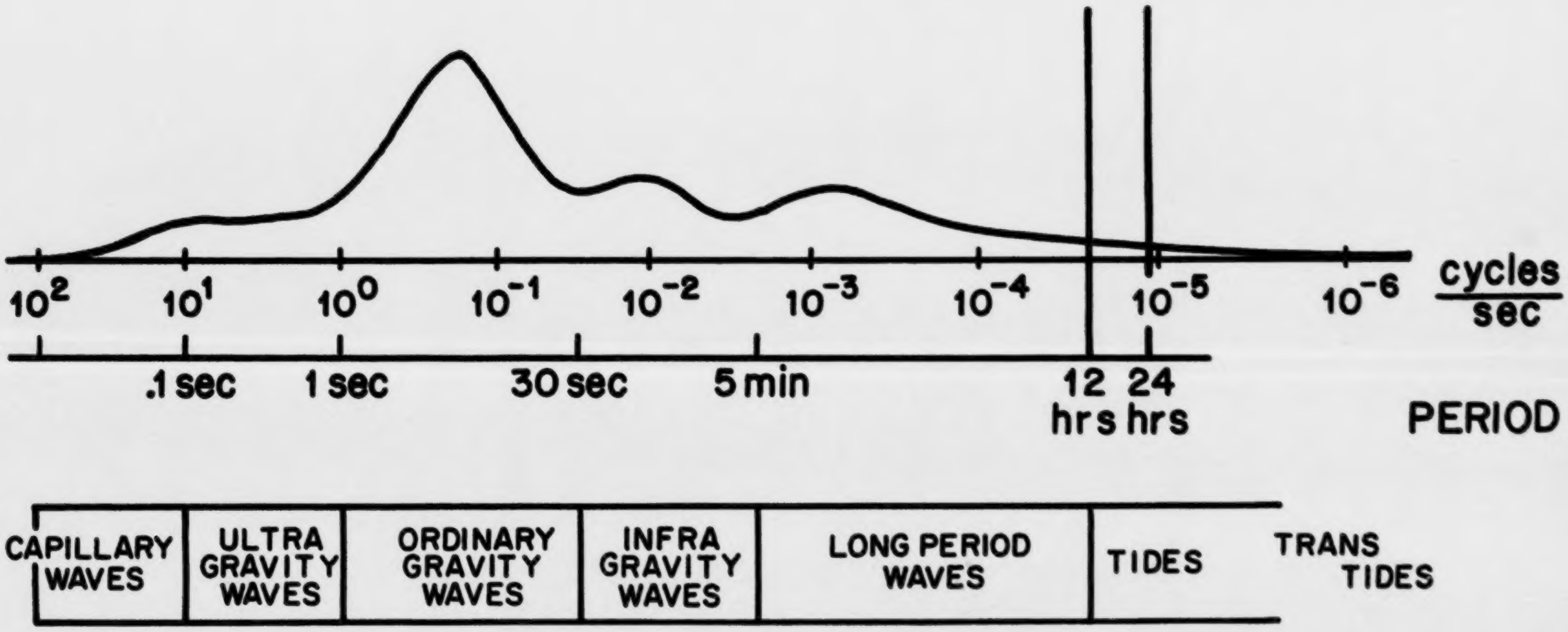

Fig. 2. Hypothetical spectrum of all surface waves on the ocean.

is merely a number representing the inverse of the period and has units of cycles per unit time. Figure 2 presents a hypothetical spectrum of all surface waves on the ocean. The vertical scale of the graph is the relative amount of energy found in the spectrum. The two horizontal scales represent wave period and wave frequency in cycles per second.

We can make some general observations about this spectrum immediately. Just as the electromagnetic spectrum has visible and invisible portions, ocean waves with periods between 0.1 and 30 seconds can be seen. Waves with periods above this range may be visually detected only in terms of their effect at the coastlimes, as in the rise and fall of the tides. Below the visible range, that is, below capillary waves, oscillatory motions fall into the realm of acoustic (sound) waves. Waves below a period of 30 seconds are generally referred to as wind-induced and have wavelengths that are much shorter than the depth of the water.

The capillary waves at the low period end of the spectrum are generated by the traction of the wind on the surface of the water, which is a function of wind speed. At inception, a slight ridge of water is formed that increases the area of the surface exposed to the wind. This permits more energy to be imparted to the water and results in what we call ripples or cat's paws. If the action of the wind persists, more energy is added and a wave system begins to grow in size and period into the ultragravity wave portion of the spectrum and beyond. This process is not always straightforward. As the ratio of the height (twice the amplitude) of a wave to its wavelength approaches 1:7, a wave becomes unatable at its crest. So, as the wind imparts energy to a wave system, the amplitudes can grow to the point of instability and cause the wave crests to break. When this happens, a portion of the wave energy is lost through turbulence and the remainder passes on to waves of higher period. As long as the energy received from the wind is greater than that lost by the turbulent action at the crest, the wave system will resume its growth. In this manner, capillary waves and ultra-gravity waves become stages of growth in the development of wind generated waves. Further, observation has shown that even in high winds, ripples and small wavelets are present on the surface of larger waves. So we should expect the entire spectrum of wind waves ultimately to be present under the continuing wind of a storm. These waves are known as sea, in contrast to swell, which consists of longer, high period wind waves from distant storms.

The relatively large amount of energy in the ordinary gravity wave band of periods represents the accumulated effect of the wind. Practically, the full development of wind waves depends not only on the wind's speed, but also on its fetch, which is the distance over which the wind acts, and on its duration. The prediction of the height of waves reaching the near shore depends on all three of these factors. At present, modern methods such as spectral analysis and the technique of receiving data from satellites are being used to extend the accuracy of wave forecasts. Wave forecasting has been going on for quite a while, however, One well-known rule was proposed by Thomas Stevenson in 1850. From his observations at the Firth of Forth in Scotland, Stevenson related the wave height (H) to the square root of the fetch (F). When the fetch is greater than 39 miles, the formula for the height given by Stevenson is

$$H\ (\text{ft}) = 1.5\ \sqrt{F\ (\text{miles})}$$

This empirical relation was used by engineers to estimate wave heights due to gale force winds until just recently. Incidentally, Thomas Stevenson has another claim to fame, a rather well-known son, Robert Louis.

The infra-gravity region of the spectrum is characterized by waves known as ground swells, surf beats, and seiches. Ground swells are generated by the wind and changes in atmospheric pressure associated with large scale storms at sea. These long, regular wave trains travel with much greater speed than the storm system from which they originate. As a result, their arrival at a coastline has long been known to warn of the approach of a storm. The origin of surf beat is not completely understood. One explanation points to the varying ability of breaking waves to transport watef towards the shore, higher waves having a greater capacity than lower ones. If groups of waves of fairly uniform height are regularly interspersed with groups of waves that are somewhat lower, a rhythmic outward surge of water will result as the lower breakers move towards the shore. Surf beat is oscillatory and has periods approximately ten times that of ordinary wind waves.

The term seiche actually covers a wide range of phenomena. In contrast to the waves discussed so far, seiches are not identified with a specific generating mechanism. Seiches are long wave oscillations triggered by any disturbance which can displace the water mass in an enclosed basin or a bay opening on a larger body of water. The waves occur when displaced water attempts to return to its equilibrium position, and they take a particular form known as standing waves. Seiches have a spectrum of their own in which the periods are multiples or harmonics of a fundamental escillation. In the fundamental standing wave, two long waves of a wavelength twice the length (L) of a basin travel in opposite directions through one another. They are superposed and form a wave which produces up-and-down movements known as antinodes at either end of the basin. Figure 3 shows the fundamental seiche node or unimodal node for a rectangular basin of uniform depth. Note that the antinodes are out of phase. Between the ends of the basin the water level has one point which does not take part in the oscillation, the node. The position of this node, the water level excursion at the antinodes, and the seiche period are critically dependent on the underwater topography and the shape of the basin (The antinodes are greatly exaggerated in the figure.) For calculations of their speeds, seiches are normally considered as long waves. The formula for the speed is given by $\sqrt{gD}$, where g is the gravitational acceleration constant and D is the depth of the water. For this calculation, the depth of the water is taken from the equilibrium position of the water. Thus the fundamental period of the seiche in Figure 3 is

$$T = \frac{2L}{\sqrt{gD}}$$

Note that the basic time interval associated with the wave is simply the basic length of the wave divided by its speed.

When one end of the basin is removed, that is, when the seiche is in a bay, the physical situation is analgous to the one in which sound waves are produced from an open organ pipe. The fundamental period for a semi-enclosed basin or bay of length L and uniform depth D is

$$T = \frac{4L}{\sqrt{gD}}$$

twice that of the equivalent basin period. The oscillation takes place around a node at the bay entrance as shown in Figure 4. A comparison of the figures will show that the seiche in the bay has a wavelength twice as long as its counterpart in the basin. Seiches in basins can be generated by atmospheric effects such as pressure changes associated with squall lines or, as in the case of the lapse of a persistent onshore wind, by the movement of a mound of water that has been pushed against the shore. Flood waters discharging into lakes and the tilting of the basin that may occur during an earhtquake also account for seiche motion. Once generated, seiches are often quite long lived, since only the small amount of friction produced at the basin bottom dissipates the waves.

Storm surges and tsunamis are typical of the waves in the long wave section of the spectrum. Tsunamis are destructive waves that comprise a progressive wave train associated with strong earthquakes. The principal sources of these waves are vertical displacements of the sea bed on the periphery of the Pacific Ocean. Due to their great length and small amplitude, it is almost impossible to see them at sea. Tsunami wavelengths are nominally those of the characteristic lengths of the seismic source and can range from tens to hundreds of kilometers. Tsunami wave amplitudes have never been measured in the deep ocean environment, but at islands, tidal records suggest that they do not exceed six feet. As long waves, their speeds are given by $\sqrt{gD}$ and this yields speeds of hundreds of miles per hour. Unfortunately, this means swift transportation of great

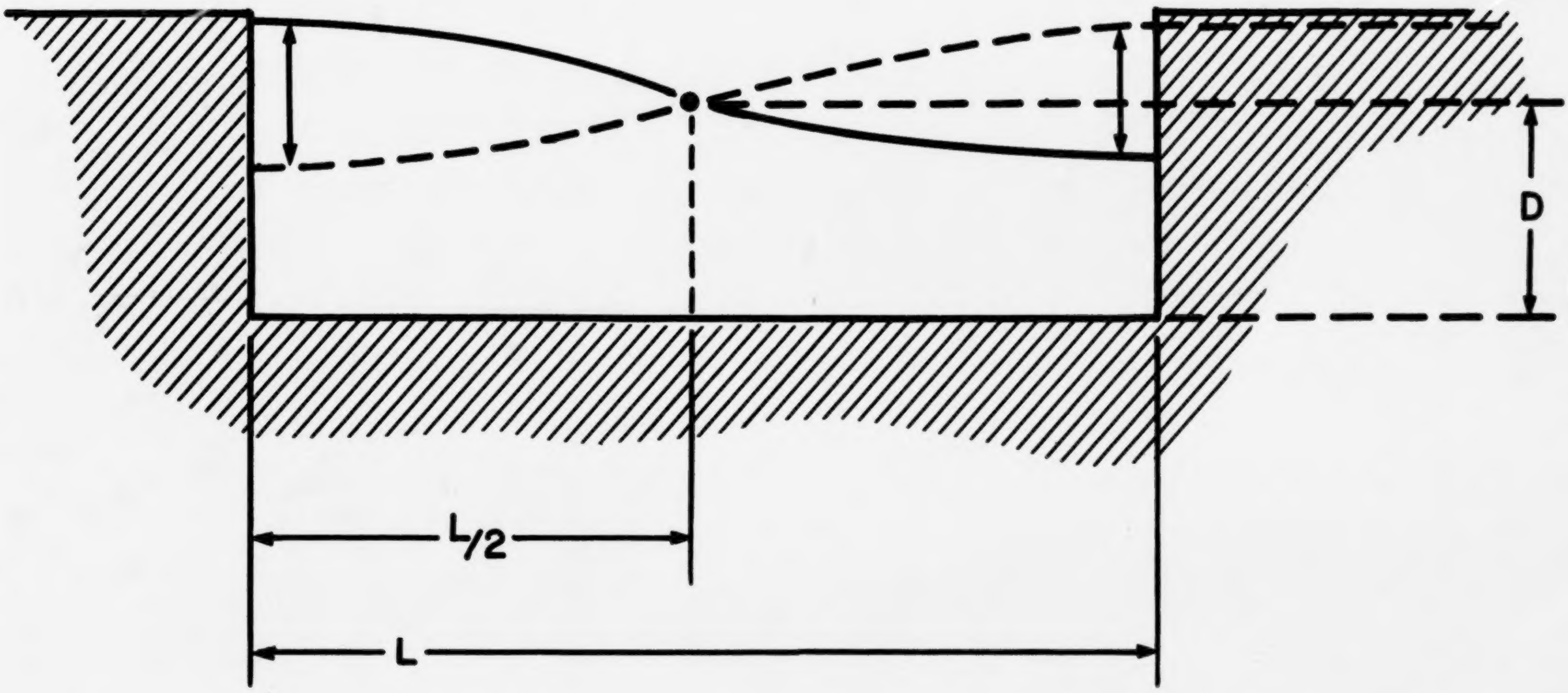

Fig. 3. Fundamental seiche node for a rectangular basin of uniform depth.

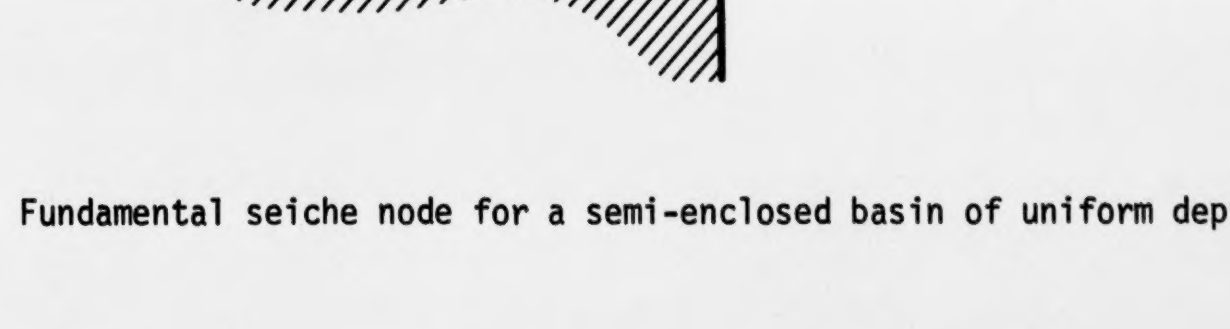
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Fig. 4. Fundamental seiche node for a semi-enclosed basin of uniform depth.

energy derived from earthquakes. At coastlines, these waves are modified by the change in depth and they increase in amplitude to produce severe flooding and, if no warning has been received, loss of life. Storm surges can cause similar inundation of low-lying lands, but they build up gradually over a longer period of time. Coupled with the storm system, a surge of this nature usually lasts for several tide cycles. It is preceded by ground swell and can have seiche-like resurgences after the storm has left the vicinity of the coast. The storm surge is primarily a response to the fluctuations of the barometric pressure generated by the storm, even though the direct action of the wind is present and a contributing factor.

Disasters produced by long period waves have been recorded for thousands of years. In recent times, a tsunami struck Jaman with waves over 100 feet high on January 15, 1896. Nearly 30,000 persons were killed by these waves, literally within minutes. The Netherlands has suffered repeatedly from storm surges. In Januray, 1953 an extremely intense storm moved south through the North Sea, towards the European coast. A combination of high winds, long fetch, very low barometric pressure, and long duration generated a ten foot water excursion over the normal high tide level. In the low-lying Netherlands, 1800 lives were lost and 800,000 acres were flooded and ruined by salt water.

Tides

The tides are the rise and fall of the ocean's waters that occurs with a predictable rhythm. They are known as astronomical tides because their generating mechanism is the gravitational attraction of the moon and the sun. The repetition associated with the sun-earth-moon system is responsible for the changes in the tides and for their principal periodic values of 12 and 24 hours. In Figure 2, the tides are shown as two large spikes of energy in the long period region.

Tides are known to be oscillatory waves which have wavelengths roughly equivalent to half the circumference of the earth. In reality, complete wavelengths will not fit into the earth's oceans because of the intervening land masses. This fact, in conjunction with relatively small wave amplitudes and the scarcity of steady observation platforms at sea, renders it difficult to obtain a complete picture of the tidal movements of the world's ocean. Therefore, tidal measurements at coastlines and isolated islands in the mid-ocean regions are the only available data and the picture is, at best, sketchy. Tide records at a given coastal position provide the data necessary for predictions of range and periodicity. The tidal excursion from mean sea level is quite dependent on the local underwater topography and ordinarily in one to three meters. In some bays and estuaries the water level is controlled by a seiche response of the water to the oceanic tide. This can lead to extreme fluctuations, such as the tidal range in the Bay of Fundy, which exceeds 15 meters.

Very early observations connected the phases of the moon with the passage of the tides. The simplest observations correlate the smallest tidal range, the neap tides, with the first and last quarters of the moon and the greatest tidal ranges, the spring tides, with the full and the new moon. Within each day, the maximum rise is known as high water and the minimum level as low water. When the water is rising, the movement is known as the flood and during the recession of the water, it is called the ebb. The average observed time interval between successive like phases is 12 hours and 35 minutes, so that high and low waters occur some 50 minutes later each succeeding day. We should expect that this basic periodicity and the phase lag would be correlated with the motion of the moon, and it is. The moon crosses a given meridian with a 50 minute lag daily.

The ocean and its movements have long held the imagination of man. Even so, in the Western world, the tides were not connected with the phases of the moon until mariners ventured from the largely tideless Mediterranean Sea and traveled along the shores of the Atlantic Ocean. As a result of these explorations, the Roman Plinius drew an accurate correlation between tides and the moon shortly after the time of Christ, but for many centuries no one could offer a convincing explanation of the means by which the distant moon could move the oceans. The answer lay in the law of universal gravitation which was formulated by Isaac Newton and published in 1687 in his monumental work the Principia. Using his law, Newton advanced an hydrostatic explanation of the tides which is known as the equilibrium theory. A number of scientists based their investigations on this method, most notably Daniel Bernoulli in 1738. The central facet of the equilibrium theory is the deformation of the ocean surface by the gravitational attraction of the sun and the moon, Thirty-six years later, Laplace put forth the first dynamic theory, one considering tides as progressive waves. William Thomson, Lord Kelvin, was the first to utilize harmonic analysis to study and predict the tides. Thomson, George Darwin, and A. T. Doodson contributed greatly to the development of this modern technique (see discussion of spectral analysis beginning on p. 78).

Newton and his contemporaties were the first to formulate the tide-raising forces generated by the gravitational attraction of the sun and the moon. Newton's law of gravitation

$$F \propto \frac{Mm}{D^2}$$

relates the dependence of the attractive force F between two masses M and m that are separated by a distance D. The equilibrium theory of the tides begins with a rotationless, spherical earth totally covered by an ocean of uniform depth. A celestial body near the earth will then cause the ocean to assume another shape due to its gravitational attraction. Newton's line of reasoning went as follows. The celestial mechanics of a two body system is based on the motion of the central body and the smaller, secondary body about their common center of gravity. Thus the earth and the moon rotate about an axis which is fixed, 3000 miles from the earth's center, by their relative masses. The system is shown in Figure 5. In the absence of diurnal rotation, the centrifugal force acting on all the particles of the earth's mass is of the same magnitude and in the same direction, away from the center of mass. The moon experiences a similar centrifugal force. These centrifugal forces acting on the earth and the moon are, on the whole, balanced by the mutual gravitational attractions. This must be so to perpetuate their association. However, on closer examination, we can discern that the attraction generated by the moon for the ocean varies. In Figure 6, at the zenith, the distance from the moon to the earth's surface is roughly 59 earth raddi, while at the nadir the distance is 61 earth raddi. This small change, reflected in Newton's law of gravity, is the central point in the equilibrium theory. The Newtonian force at the zenith is greater than it is at the nadir. Indeed, at the zenith, the Newtonian force exceeds the centrifugal force and the earth's ocean is pulled toward the moon. The centrifugal force at the nadir is greater than the Newtonian force and once again the ocean is pulled away from the earth. The result of combining these forces over the earth is shown in Figure 7, where the length of the arrow indicates the relative strength of the force. Calculations show that the forces produced at the zenith and nadir are very nearly equal to one another in magnitude.

Any force may be resolved into components and we will consider the forces shown in Figure 7 in terms of a component vertical to the ocean surface and one parallel to the surface. The vertical component produces no motion in the horizontal direction and is of little consequence in the study of the tides. The horizontal component is the tractive force which acts on the ocean and produces the equilibrium tide. Clearly, at the zenith, the nadir, and midway between, the tractive, tide-generating force vanishes. Figure 8 shows the variation of this force on the surface of the ocean. Notice that it assumes its greatest value on the latitudes that are 45 degrees from the zenith and the nadir and that everywhere within a given hemisphere the ocean is impelled toward the pole. Without considering the motion of the water, the ocean will take an equilibrium shape under the action of this field of force. The new shape can be mathematically derived and is geometrically known as an oblate spheroid (overweight football).

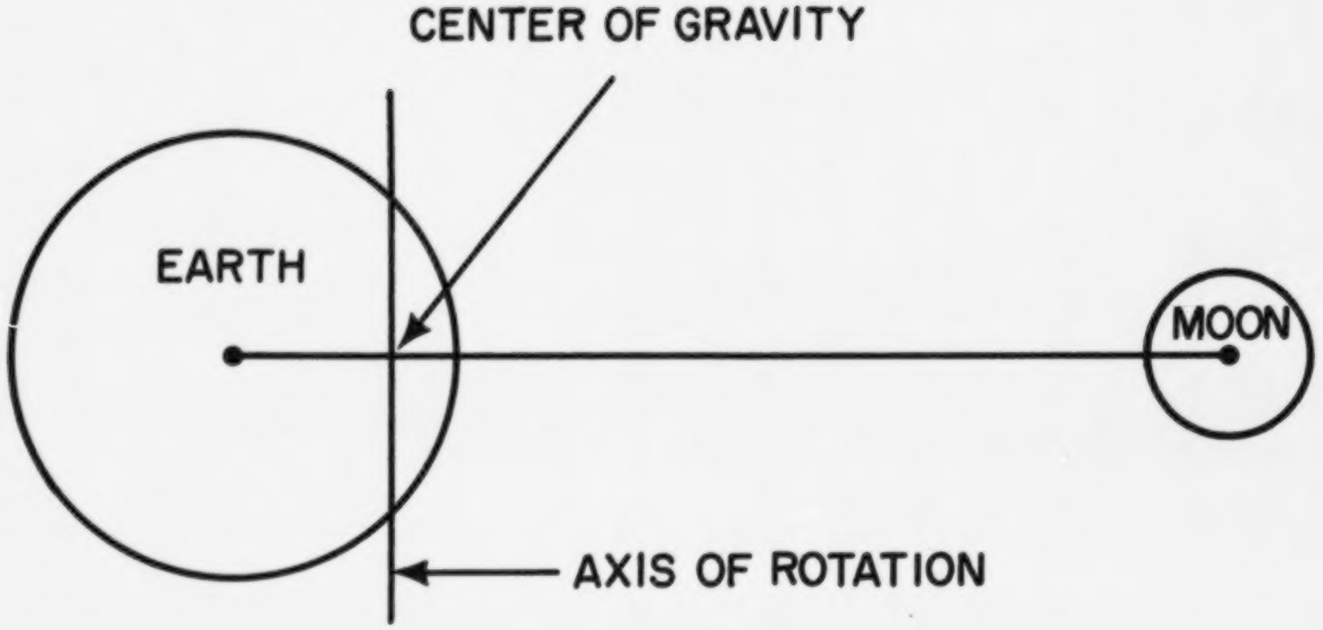
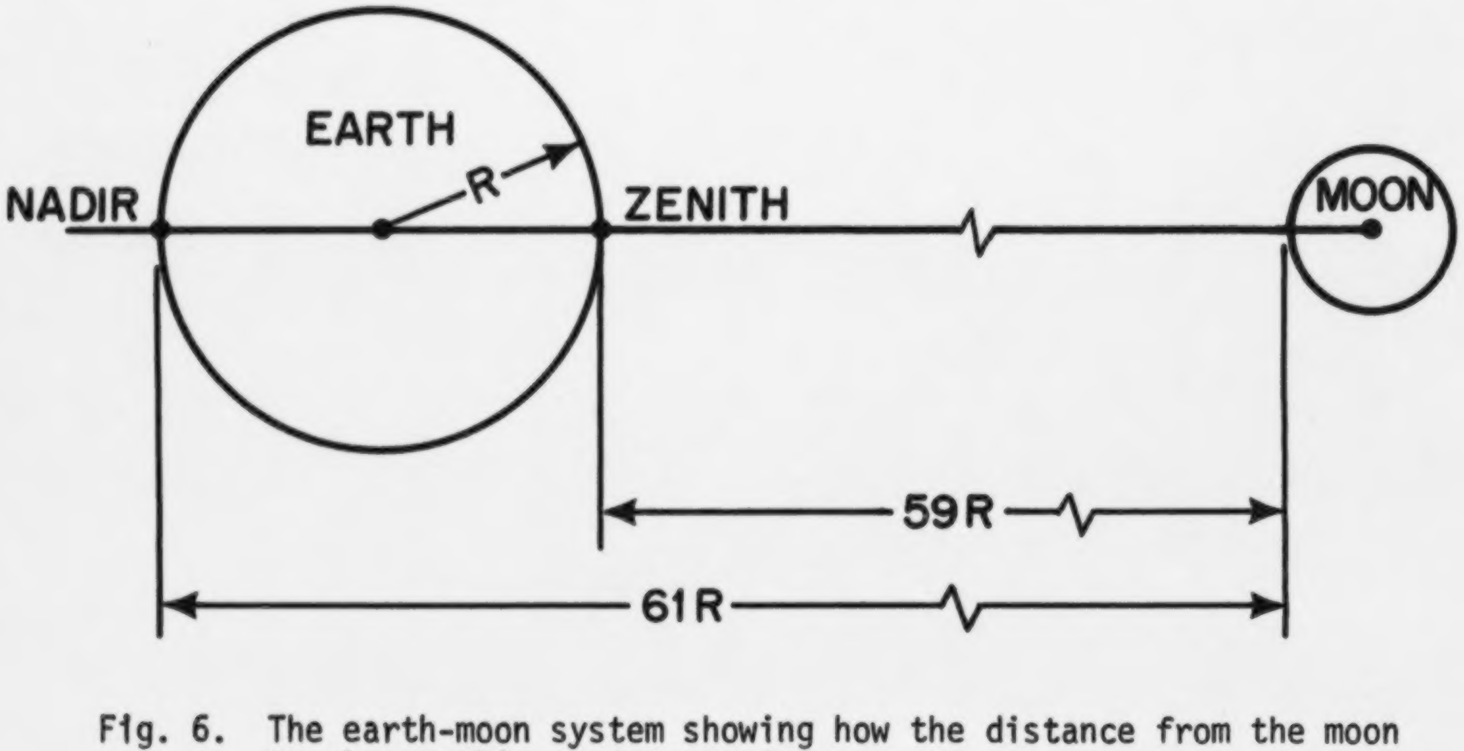

CENTER OF GRAVITY
EARTH
MOON
AXIS OF ROTATION

Fig. 5. The earth-moon system showing the common center of gravity and axis of rotation.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ZENITH
MOON
59R
61R

Fig. 6. The earth-moon system showing how the distance from the moon to the earth's surface varies.

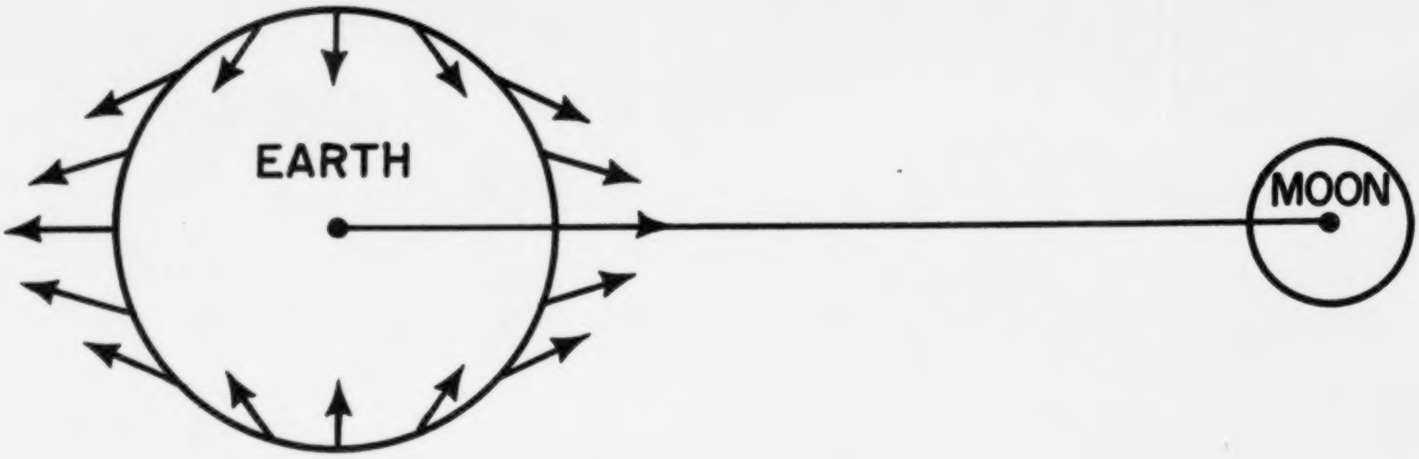


Fig. 7. The relative strength and direction of the tide-generating force. (after Darwin, 1911)

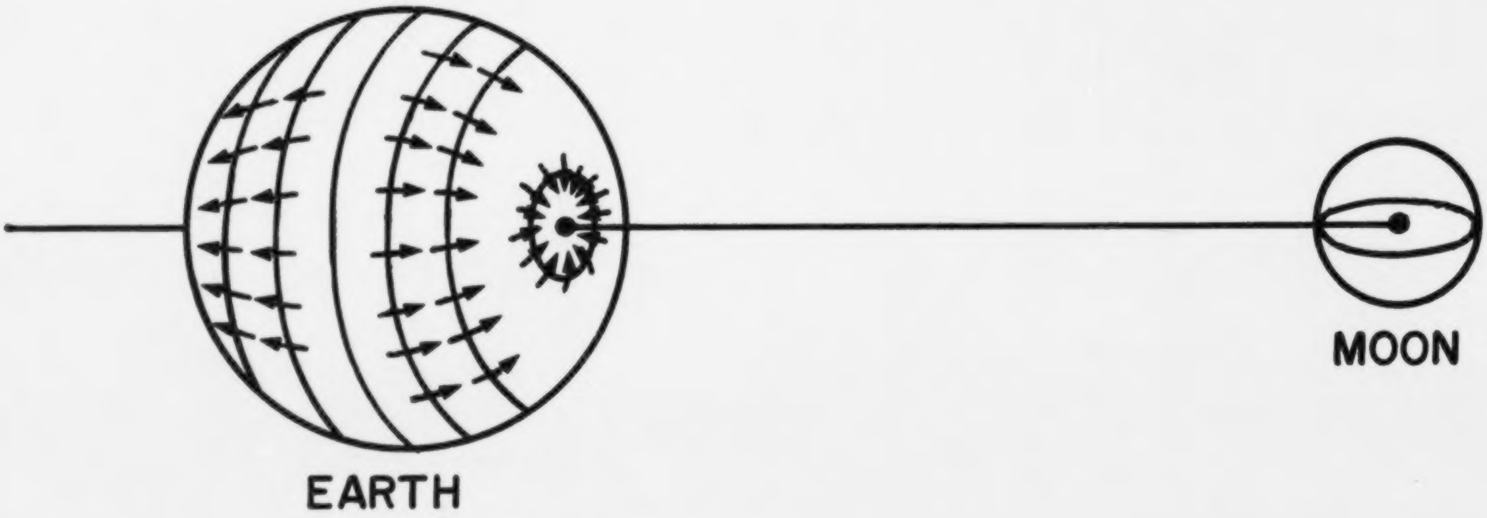


Fig. 8. The variation of the horizontal component of the tide-generating force. (after Darwin, 1911)

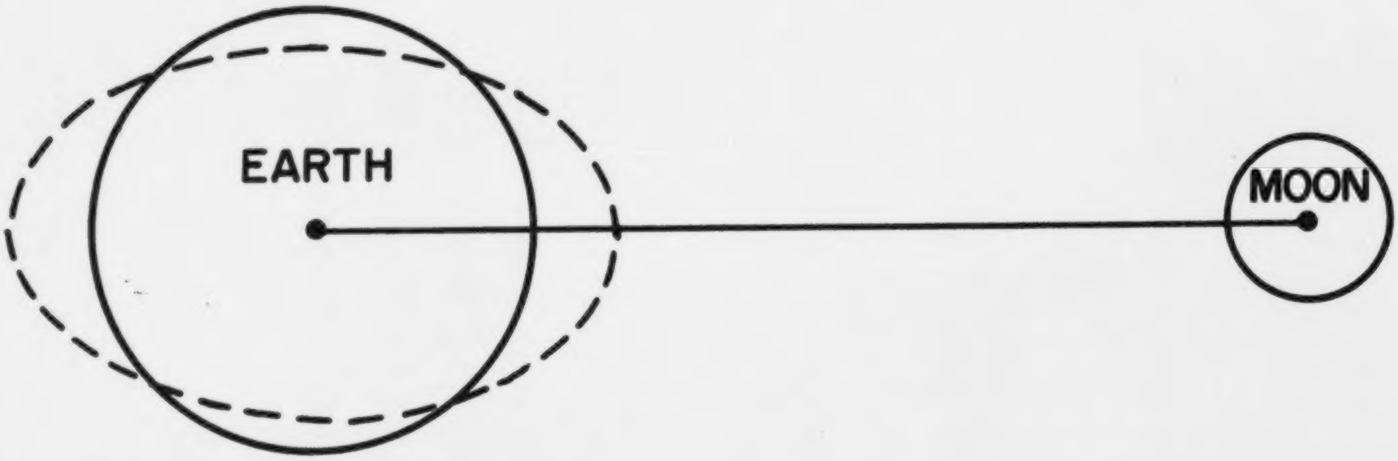


Fig. 9. Equilibrium tide, greatly exaggerated.

The ocean bulges at the zenith and the nadir and is shallower at the mid-point or equator. An equilibrium tide is shown as the dashed line in Figure 9. Oceanographers refer to this shape as the tide potential of a celestial body.

We have shown the derivation of a lunar equilibrium tide. A similar tide is associated with the earth-sun system although it is somewhat smaller in magnitude. The magnitude of the solar tide, T_s, is related to the lunar tide, T_m, by

$$T_s = \frac{M_s}{M_m}\left(\frac{D_m}{D_s}\right)^3 \simeq 0.46$$

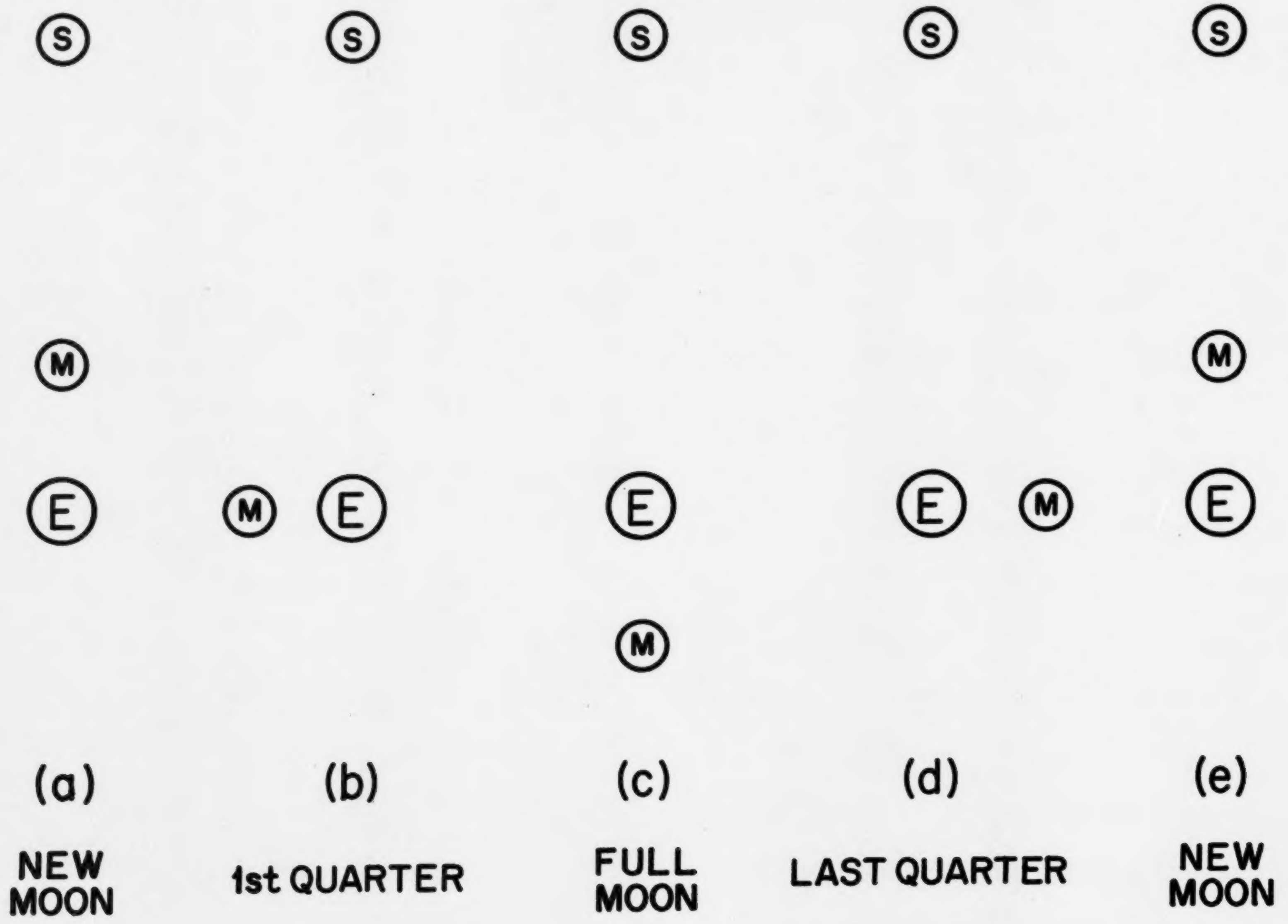
Where M_s, M_m are the masses of the sun and the moon and the distances D_m, D_s are measured from the center of the earth to the centers of the moon and the sun, respectively. So we have the result that the lunar tide is, on the average, roughly twice that of the sun. On our model earth, the maximum tides predicted by the equilibrium theory are about 35 centimeters (14 inches) for thelunar tide and about 16 centimeters (6 inches) for the solar tide. These results probably come closest to reality in water of oceanic depths far from the influence of land masses.

So far we have developed a static theory which gives us an idea of the basic forces operating to produce the tides. We can now begin to examine more subtle aspects. The rotation of the earth brings a given meridian beneath the sun once every 24 hours, the mean solar day. Successive solar high tides are then simultaneously generated at the zenith and the nadir every 12 hours. This is the period of the solar tide. If we begin with the sun, the earth, and the moon in conjunction, as is shown in Figure 10 (a), 29½ solar days must elapse before the three bodies again achieve this juxtaposition, Figure 10 (e). During one solar day, the moon must then travel around the earth an angular distance of $2\pi/29.5$ radians. A given meridian would have to turn through $2\pi + 2\pi/29.5$ radians daily to keep up with the moon. Since the earth turns through only 2π radians each day, the moon crosses each meridian 50 minutes later each day. For the lunar tide, the result is a period of 12 (1 + 1/29.5) hours, or approximately 12 hours and 25 minutes. As we have noted, observation has confirmed that the high tides, on the average, occur approximately every 12 hours and 25 minutes.

The slight difference in the lunar and solar tide period gives rise to the monthly tide cycle. Beginning with conjunction, the lunar tide lags behind the solar tide by 0.8 hour for each successive day. In approximately 7½ days the lag has grown to six hours and the moon has passed around the earth to the position shown in Figure 10 (b). The maximum opposition of the tide-raising forces of the moon and the sun occurs here. Therefore, a neap tide results at the first quarter of the moon. Mathematically, this is the point of maximum interference of two waves of different amplitudes and periods, the lunar and the solar tide waves. A simple extrapolation of these arguments will permit the reader to generate the entire cycle of the high and low tide ranges.

So far we have examined the tidal generating mechanism from the standpoint of a simple model, an hydrostatic deformation of the ocean's surface. A more complete picture of the tide can be achieved with a dynamic model in which the primary responses of the ocean are progressive long waves. Recall that the equilibrium theory presumes the earth to be completely covered by an ocean of uniform depth. In reality, the continents and underwater topography play a major role in the development of the tide by modifying the progressive long waves.

Let's consider the North Atlantic Ocean. As the earth turns from west to east, a point directly beneath the moon will move across the ocean from east to west. Progressive long waves are generated which move from the European shore toward North America, associated with either the zenith or the nadir, once every 12 hours. As the continental slope, these waves are reflected with very little diminution in amplitude and, by interacting with incoming waves, tend to set up a standing wave system known as the co-oscillating tide. As we noted in the section on waves, simple standing waves have characteristic modal points that are fixed in space. Observation has suggested that similar nodes exist in the oceanic tides.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E
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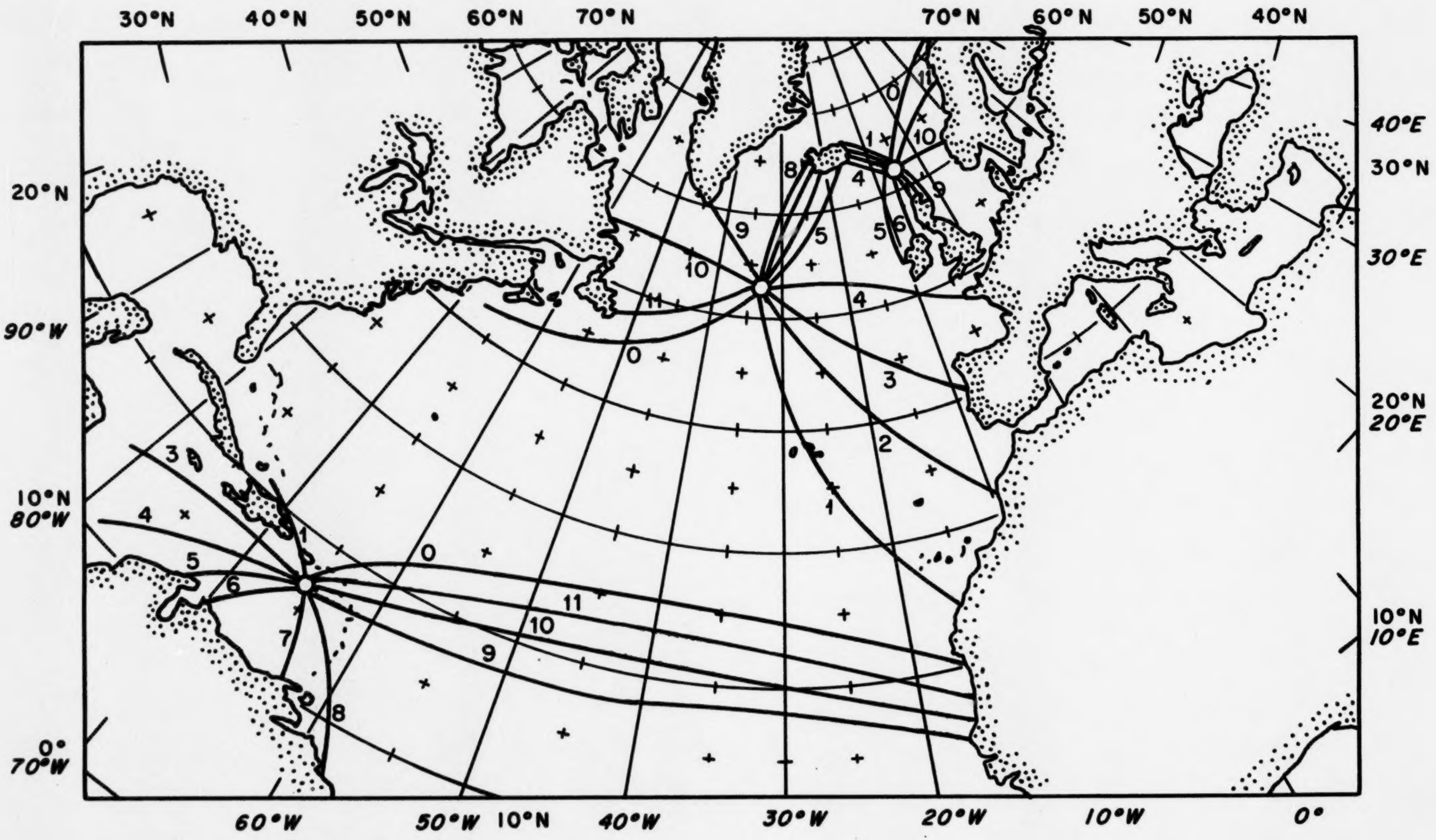
(a)
(b)
(c)
(d)
(e)
NEW MOON
1st QUARTER
FULL MOON
LAST QUARTER
NEW MOON

Fig. 10. The relative positions of the sun, the moon, and the earth during the lunar cycle.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40°N
50°N
60°N
70°N
70°N
60°N
50°N
40°N
20°N
90°W
10°N
80°W
0°
70°W
40°E
30°N
30°E
20°N
20°E
10°N
10°E
60°W
50°W
10°N
40°W
30°W
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11

Fig. 11. The principal lunar and solar tide in the North Atlantic Ocean.

The development of nodes in the co-oscillating tide is strongly influenced by the rotation of the earth about its axis. In oceans such as the North Atlantic, the earth's spin gives rise to rotational wave motion that modifies the simple progressive wave picture. To see how this happens, imagine an ocean-sized cylindrical basin of water that is not rotating. When tilted slightly, the water will be high on one side (approximating the tide potential) and when righted, the water will move directly from one side to the opposite side in a sloshing motion. A nodal line extending completely across the basin will exist midway between the sides. Now if the tilted basin is on an earth rotating from west to east and is righted, the high water will not move as before, but will generate a wave traveling around the basin in the sense of its rotation. In this case the nodal line must also rotate so that a complete circuit of the wave around the basin defines a single nodal point in the centre. For the oceanic tides a number of these points are present and are known as amphidromic points of the co-oscillating tide. These may be regarded as rotational features at which no tide is experienced. The tides in the North Atlantic Ocean are influenced by three amphidromic points. In Figure 11 a rough sketch of the tide is presented and these points are shown as open circles with lines radiating from them that are called co-tidal lines. Co-tidal lines join points of equal phase for the rotating tide waves and are drawn at one hour intervals in this figure. The significance of 12 lines about each node should be apparent. For example, a high tide occuring at co-tidal lines 3 (Caribbean, Portugal, Iceland) occurs simultaneously with low tides along lines 9 (Cape Verde, Greenland, Scotland). One hour later, the high tides would be along lines 4 and the low tides on lines 10. As a point of emphasis, we should remember that the observational evidence for this co-oscillating picture of the tides is taken mainly on continental shores. Recent tide studies using electronic computers have stimulated studies of data for hitherto unresolved amphidromic points. One such point was "found" in the South Atlantic Ocean by computation and has been tentatively identified in the tide observations of the area.

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6. OCEANIC CIRCULATION

by Lynn Forbes
Oceanographic Education Center

Causes and General Description

The energy that drives oceanic circulation comes from the sun. Its radiation causes winds to blow and makes water in one place more dense than water in another. In combination, the winds and changes in density set up forces that move the water around in the ocean.

The density of sea water depends on its temperature and its salinity, and it will become more dense and begin to sink as it becomes colder and saltier. Salinity can be increased through evaporation or freezing. In both cases, water is removed from the surface layers (as vapor in the first instance and as ice in the second)leaving a saltier solution behind. However, an increase in salinity through evaporation is not very effective in initiating circulation. The resulting increase in density is usually balanced by a decrease due to a rise in temperature and the saltier water remains on the surface. Cooling and the formation of ice, then, are the principal causes of density-driven circulation. A flow will result whenever a mass of dense water overlies water that is less dense. The senser water will sink beneath the surface until it encounters a layer of even denser water or until it reaches the bottom.

Most of the deep and bottom waters of all the oceans are formed in polar seas adjacent to the North and South Atlantic Oceans. Here, the surface waters sink because they have become relatively dense either from cooling or because ice has frozen out. They spread slowly towards the equator filling the central ocean basins, and they are replaced by water that rises from intermediate depths and spreads towards the poles. Thus, the typical direction of motion resulting from changes in density is vertical and the initial downward motion in one area is compensated for by an upward motion in another. Great masses of water with characteristic temperatures and salinities flow in between, spreading horizontally at different levels either north or south. It is probable that the horizontal flows are unevenly distributed, being stronger on the western sides of the oceans. It is not certain whether all of the deep waters are being formed continuously or whether most of them have sunk only at certain times when the climate has been extremely cold.

Water masses are identified and their movements traced chiefly by their physical properties and by their chemical characteristics, which they retain to a remarkable degree over long distances and periods of time. They are classified according to relative depth as bottom, deep, intermediate, and surface waters. Surface waters extend to depths of only a few hundred meters and they are distinguished from the deeper waters in that their motion is affected directly by the wind.

Water that flows under the stress of the wind, moves horizontally, but in the open ocean at least, it does not move in the same direction as that in which the wind is blowing. Rather, the flow is deflected by the effect of the earth's rotation (the Coriolis force) in a direction 45° to the right of the wind direction or clockwise in the northern hemisphere abd 45° to the left or counterclockwise in the southern. The wind, however, impinges only on the surface. Its force is translated downward with diminishing effect to each succeeding layer of water by the one immediately above it. The result is that at increasing depths the water is transported farther and farther to the right (or the left) of the wind, but with decreasing speed. Theoretically, if the water is deep enough (100 to 300 meters) and the land does not interfere, and if there are no conflicting deep water motions, the net transport of water under the influence of the wind is at an angle of 90° to the direction of the wind, to the right in the northern hemisphere and to the left in the southern.

In certain areas of the surface layer, the typically horizontal motion of the water develops into swift and concentrated flows. The surface flow of the Gulf Stream, in which the water can attain a speed of five knots, is a notable example. Such well defined streams are described as currents, a term which is not usually applied to the slow and stately motions which characterize the deeper waters, but which is often extended to include horizontal movements that are distinctly more diffuse than those of the Gulf Stream.

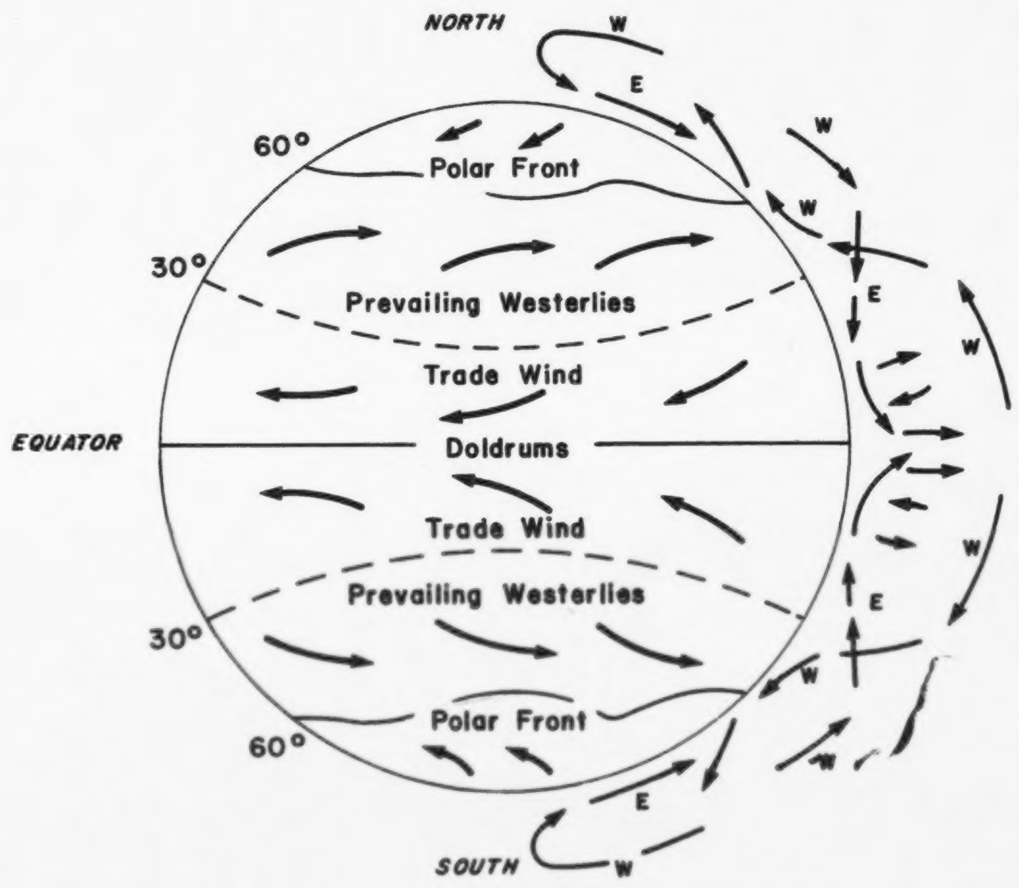
Figure 1 shows the prevailing direction of the winds near the earth's surface in the three principal wind zones of each hemisphere. It can be seen that if the winds and the Coriolis force were the only influences on surface circulation, currents would flow around the earth in alternating bands going east and west. The only place where this actually happens is in the Antarctic Ocean, where the major current flows eastward around the globe. In the rest of the ocean, the continents are in the way. The effect of the continents and the Coriolis force combine to set up great clockwise circulations in the northern hemisphere and corresponding counterclockwise gyres in the southern (Figure 2).

The gyres originate in the broad bands of currents flowing westward north and south of the equator and they are set in motion by the trade winds, which blow more steadily than those in the earth's other wind belts. In the northern hemisphere, the westward flowing currents are deflected northward (to the right) along the eastern margins of the continents. As they approach the latitudes of the prevailing westerly winds they again trend right and flow eastward towards the western seacoasts of the continents. Here, they turn right yet again, moving southward to feed back into the current flowing westward along the equator. The same thing happens in the southern hemisphere except that the Coriolis force causes the currents to turn constantly to the left. The clockwise gyres of the northern hemisphere are separated from the counterclockwise gyres in the southern by narrow countercurrents that run eastward along the equator in the region of the doldrums.

Although it appears that the wind is the principal agen of motion in the surface layer of ocean water and that density changes are chiefly responsible for circulation in the deeper layers, the situation is not quite so simple as that. The ocean is continuous. Masses of water moving in one direction encounter masses of water moving in another and the two interact as they flow past one another. It is possible for the wind itself to cause imbalances in the distribution of density by blowing cold water overtop of that which is warmer. On the other hand, any dense water that has sunk from the surface and is flowing at depth must exert an influence on the motion of the water above it. For the sake of convenience, the two driving mechanisms have been discussed separately, but it should be remembered that for a given case it is not always possible to tell which of the two is predominant. The motions caused by density changes and the motions induced by wind interact, and any separation is, to some extent, arbitrary.

Surface Currents

Since the Antarctic Ocean (Figure 3) is continuous with all the other oceans and interacts directly with each, its system of currents will be described first. In a narrow zone near the coast, weak currents flow westward under the influence of the prevailing easterly winds. Farther away from the continent, the grand Antarctic Circumpolar Current or West Wind Drift moves eastward around the globe. It is driven largely by the frictional stress of the westerly wind which predominates in the latitudes between 60° S and 40° S. The Coriolis force contributes a northward component to this broad current which gives rise to the Antarctic Convergence, a zone circling the continent at about 50° S latitude in which some of the cold, dense Antarctic waters sink beneath the surface. A second region of sinking farther north, the Subtropical Convergence, defines the line along which the currents flowing south in the Atlantic, Pacific, and Indian Oceans merge with the West Wind Drift. Their average positions are shown in Figure 4. Sinking also takes place immediately off the coast, particularly in the Weddell Sea. The boundary between the westward flowing currents near the margin of the continent and the eastbound Circumpolar Current marks an area of divergence where deep waters are rising to the surface. These rising and sinking motions serve to keep the nutrients, which normally sink slowly to the bottom, circulating in the upper waters of the Southern Ocean, making it one of the most fertile ocean areas in the world.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30°
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Polar Front
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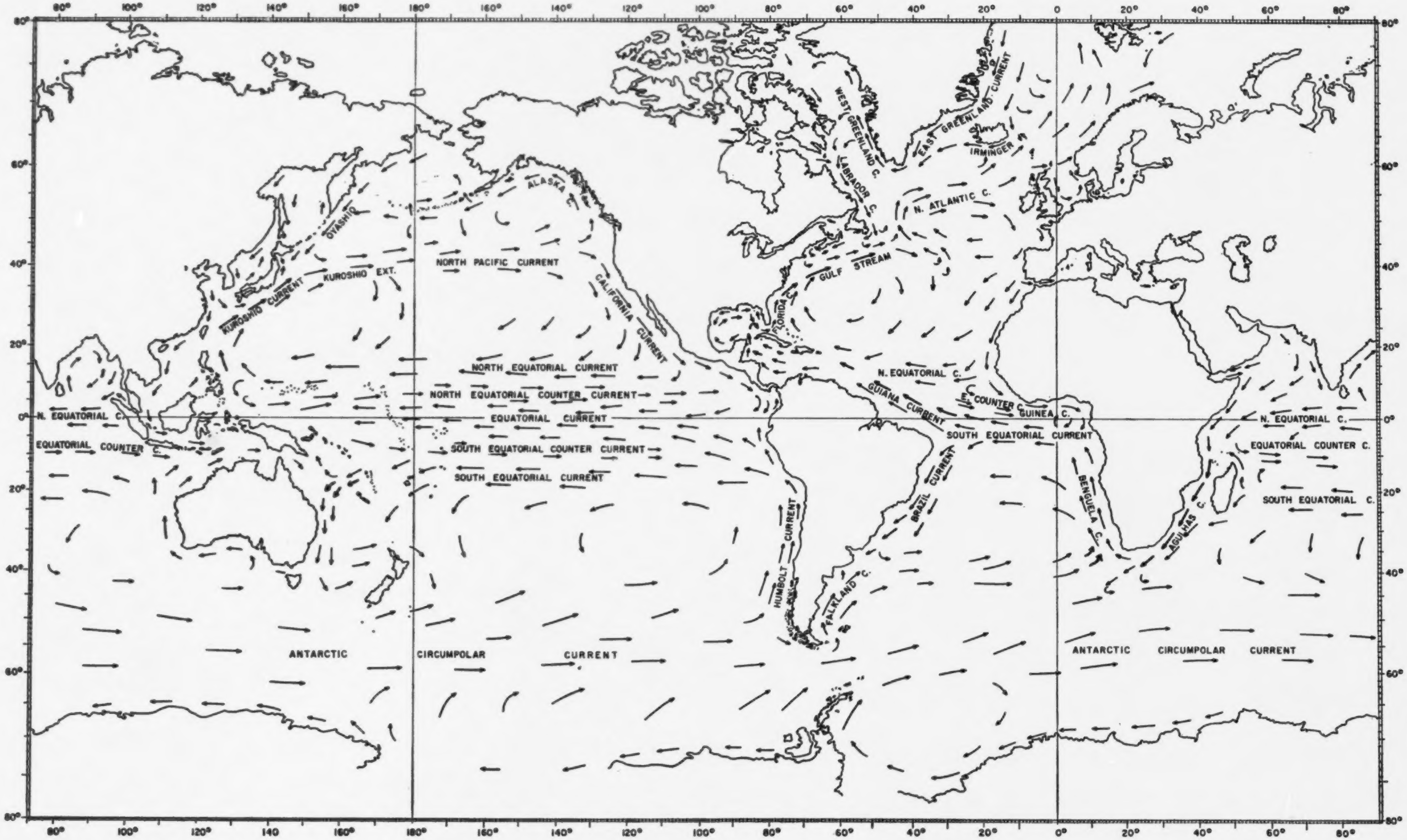
Figure 1. Prevailing direction of the winds at the surface of the earth, including a representation of north-south circulation. (From William S. von Arx.)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KUROSHIO CURRENT
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NORTH PACIFIC CURRENT
CALIFORNIA CURRENT
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SOUTH EQUATORIAL COUNTER CURRENT
SOUTH EQUATORIAL CURRENT
N. EQUATORIAL C.
EQUATORIAL COUNTER C.
WEST GREENLAND C.
LABRADOR C.
EAST GREENLAND CURRENT
IRMINGER
N. ATLANTIC C.
GULF STREAM
FLORIDA
N. EQUATORIAL C.
GUIANA CURRENT
E. COUNTER C.
GUINEA C.
SOUTH EQUATORIAL CURRENT
BRAZIL CURRENT
HUMBOLT CURRENT
FALKLAND C.
BENGUELA C.
AGULHAS C.
N. EQUATORIAL C.
EQUATORIAL COUNTER C.
SOUTH EQUATORIAL C.
ANTARCTIC
CIRCUMPOLAR
CURRENT
ANTARCTIC
CIRCUMPOLAR
CURRENT

Figure 2. Major features of the surface circulation of the oceans. The currents of the Indian Ocean are shown as they exist from November through March, otherwise the map shows average conditions for no particular time of year. (From Hugh J. McLellan.)

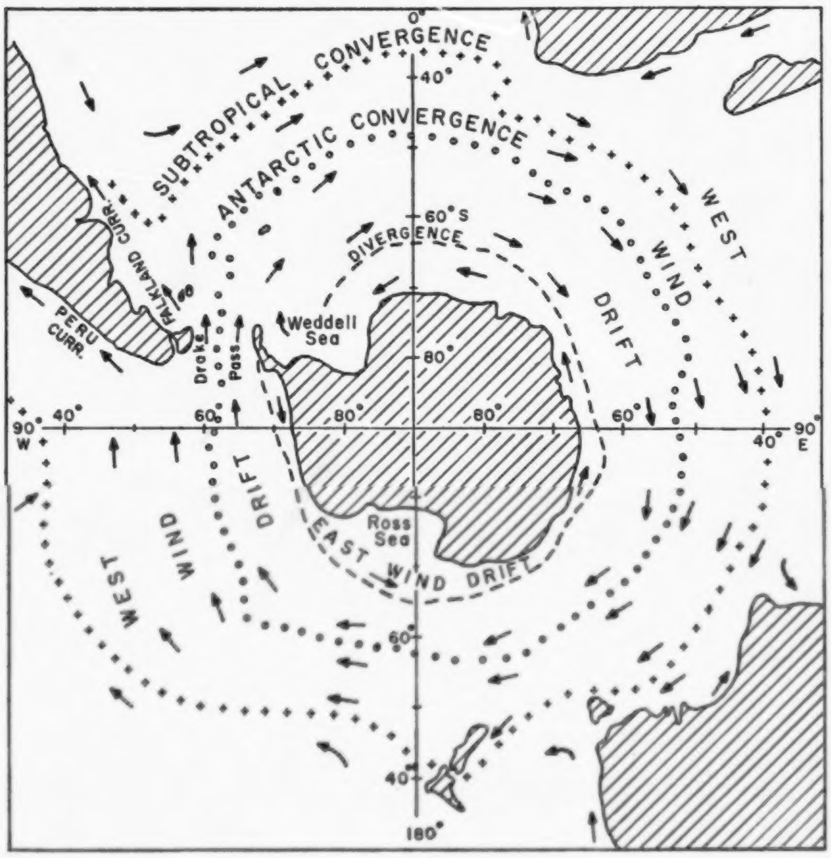
0°
SUBTROPICAL CONVERGENCE
ANTARCTIC CONVERGENCE
40°
60°S
DIVERGENCE
80°
WEST WIND DRIFT
FALKLAND CURR.
PERU CURR.
Drake Pass.
Weddell Sea
90° W
40°
60°
80°
80°
60°
40°
90° E
Ross Sea
EAST WIND DRIFT
WEST WIND DRIFT
60°
40°
180°

Figure 3. Antarctic Ocean - Surface circulation and mean positions of the Antarctic and Subtropical Convergences. (From George L. Pickard.)

In contrast with the Antarctic, the Arctic Sea is practically surrounded by land and water does not flow freely in and out of the openings that do exist. Its passage is restricted by sills that rise relatively close to the surface across the connections with the Atlantic and Pacific Oceans. The connection with the Pacific is especially shallow and narrow, and, though some water enters the Arctic through the Bering Strait, most of it flows in around Spitsbergen and out past the northeast tip of Greenland. Circulation within the sea itself is quite complicated, as illustrated in Figure 4. The Lomonosov Ridge, which divides the Arctic into two basins along a line which extends across the North Pole from Greenland to Siberia, especially restricts the flow of the deep waters.

The circular flow of surface waters in the South Atlantic (Figure 5) begins in the region of the southeasterly trade winds. Here the South Equatorial Current moves westward towards South America. Part of the current turns northward off the coast of Brazil and passes across the equator into the North Atlantic. The rest turns south along the coast of South America as the warm, saline Brazil Current. This turns eastward and the circulation continues as part of the West Wind Drift to the southern tip of Africa where the cold, less saline Benguela Current runs up the coast feeding back into the South Equatorial Current. Some water enters the South Atlantic through the Drake Passage and travels up the coast of Argentina. Another contribution arrives from the Indian Ocean, flowing round the Cape of Good Hope and augmenting the Benguela Current.

The North Atlantic gyre (Figure 5) originates in the North Equatorial Current which flows westward in the region of the northeasterly trades. It is joined in the west by the part of the South Equatorial Current that passes northward across the equator. It then splits and part of the water flows outside the West Indies while the rest flows through the Caribbean into the Gulf of Mexico. This portion passes through the Gulf and goes out between Florida and Cuba as the Florida Current. The two parts rejoin off the east coast of Florida and continue northeastward as the Gulf Stream from Cape Hatteras to the Grand Banks off Newfoundland. The more diffuse current flowing northeast from this point is referred to as the North Atlantic Current. Part of this current turns northward between

Scotland and Iceland and continues into the Arctic. The remainder goes down past Spain and North Africa and flows back into the North Equatorial Current. Separating the North Atlantic gyre from that in the South Atlantic is the Equatorial Countercurrent which runs eastward towards the African coast between the North and South Equatorial Currents. There is also evidence of an Equatorial Undercurrent flowing in the opposite direction below the surface.

The conspicuous feature of the North Atlantic surface circulation is the swift and concentrated flow on the west, represented by the Florida Current and the Gulf Stream, which contrasts sharply with the broad and ill-defined southward flow over most of the rest of the ocean. Nevertheless, the Gulf Stream does not flow in a consistent, well marked channel as "a river in the ocean." This warm, relatively saline current more nearly resembles a sinuous series of filaments of current which are usually changing course and meandering, and sometimes breaking away altogehter. There is some evidence of a strong, southwest countercurrent flowing deep beneath the swiftly moving surface waters. However, the most recent evidence indicates that the Gulf Stream extends all the way to the bottom, and that the subsurface countercurrent is either intermittent or is flowing parallel to the Gulf Stream on the inshore side.

At the surface, the Gulf Stream is separated from the coast of North America by relatively cool water which flows southwestward along most of its length. This is fed partly by the Labrador Current which, in turn, is a continuation of the surface outlfow from the Arctic. The largest volume of water coming out of the Arctic passes along the surface down the east coast of Greenland, around the southern tip, and up the west coast. This current joins the Arctic water flowing down through the Canadian Archipelago and continues south as the Labrador Current. Off the coast of Newfoundland, most of this feeds into the North Atlantic Current, but some of its cold water is sent down along the northeastern coast of the United States as far as Cape Hatteras.

It has been widely reported that relatively saline water at the surface east of the southern tip of Greenland which sinks as a result of winter cooling supplies most of the deep water of the North Atlantic.

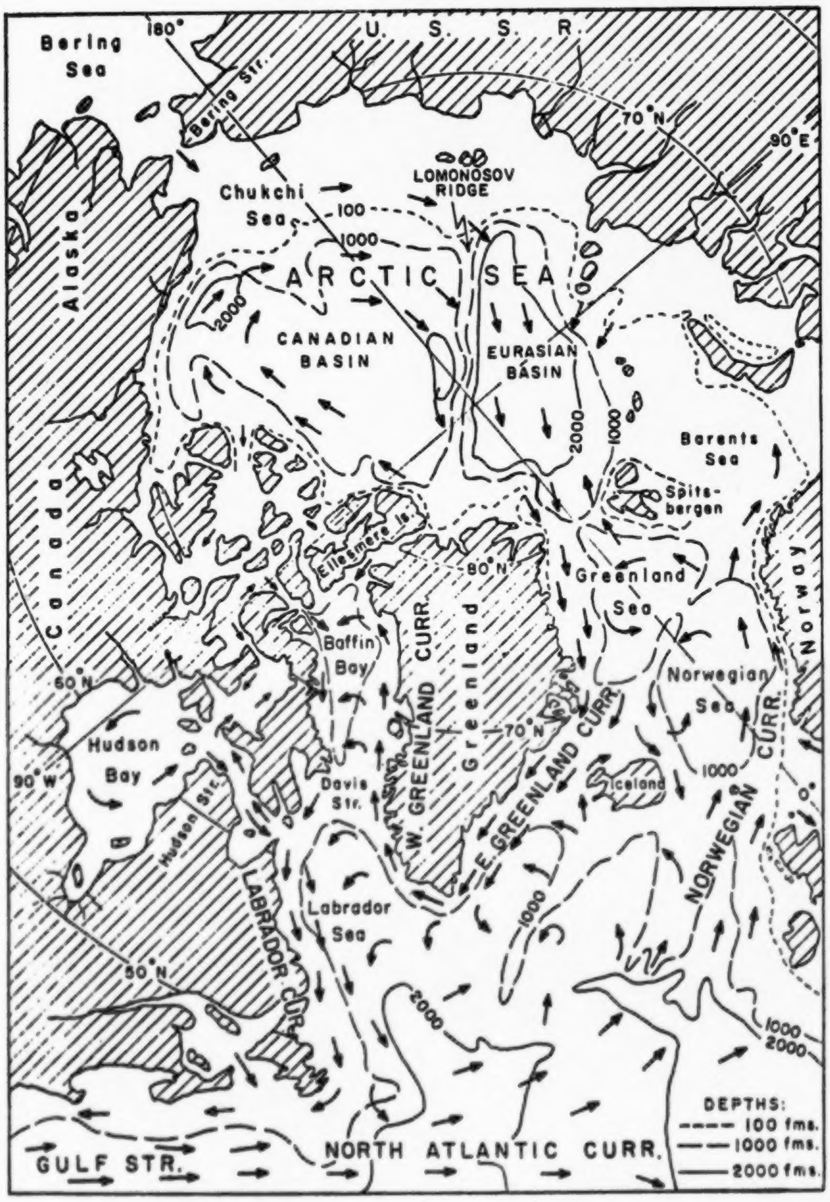
Bering Sea
180°
U. S. S. R.
Bering Str.
70°N
90°E
Alaska
Chukchi Sea
LOMONOSOV RIDGE
100
1000
2000
ARCTIC SEA
CANADIAN BASIN
EURASIAN BASIN
Barents Sea
Spitsbergen
Canada
Ellesmere Is.
90°N
Greenland Sea
Norway
Baffin Bay
W. GREENLAND CURR.
Greenland
60°N
70°N
E. GREENLAND CURR.
Norwegian Sea
Hudson Bay
90°W
Hudson Str.
Davis Str.
Iceland
NORWEGIAN CURR.
LABRADOR CURR.
Labrador Sea
50°N
DEPTHS:
100 fms.
1000 fms.
2000 fms.
GULF STR.
NORTH ATLANTIC CURR.

Figure 4. Arctic Sea and North Atlantic adjacent seas - surface currents and general bottom topography. (From George L. Pickard.)

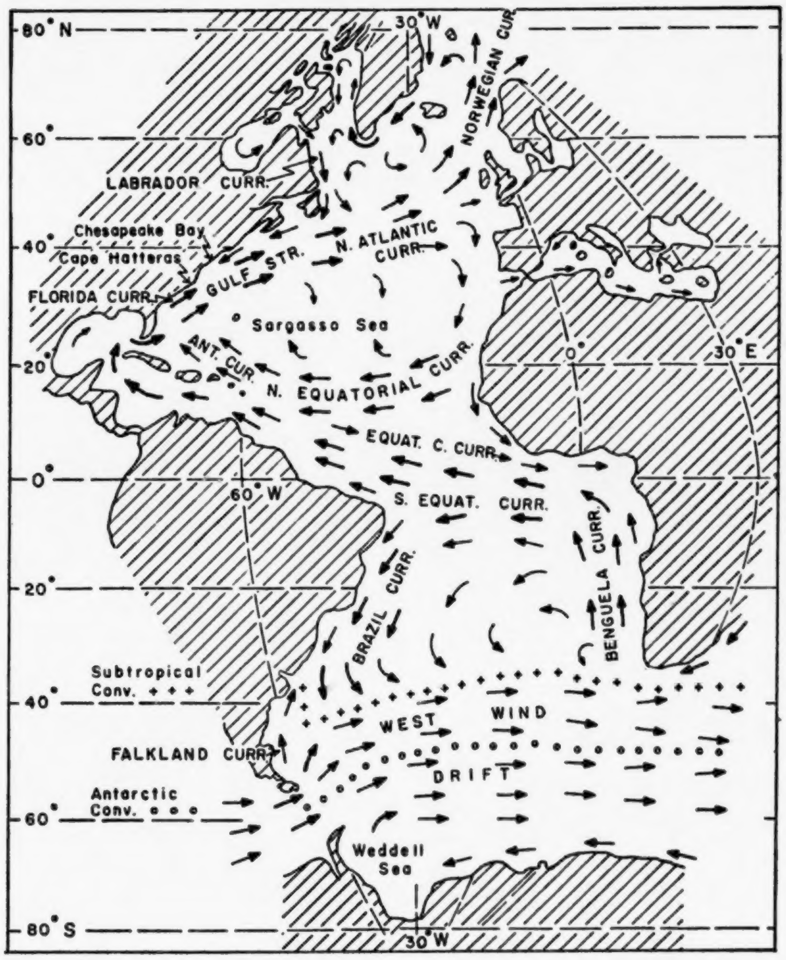
80° N
30° W
NORWEGIAN CUR.
60°
LABRADOR CURR.
Chesapeake Bay
Cape Hatteras
40°
GULF STR.
N. ATLANTIC CURR.
FLORIDA CURR.
Sargasso Sea
ANT. CUR.
N. EQUATORIAL CURR.
20°
0°
30° E
EQUAT. C. CURR.
0°
60° W
S. EQUAT. CURR.
BENGUELA CURR.
20°
BRAZIL CURR.
Subtropical Conv. + + +
40°
WEST WIND DRIFT
FALKLAND CURR.
Antarctic Conv. o o o
60°
Weddell Sea
80° S
30° W

Figure 5. Surface circulation of the Atlantic Ocean. (From George L. Pickard.)

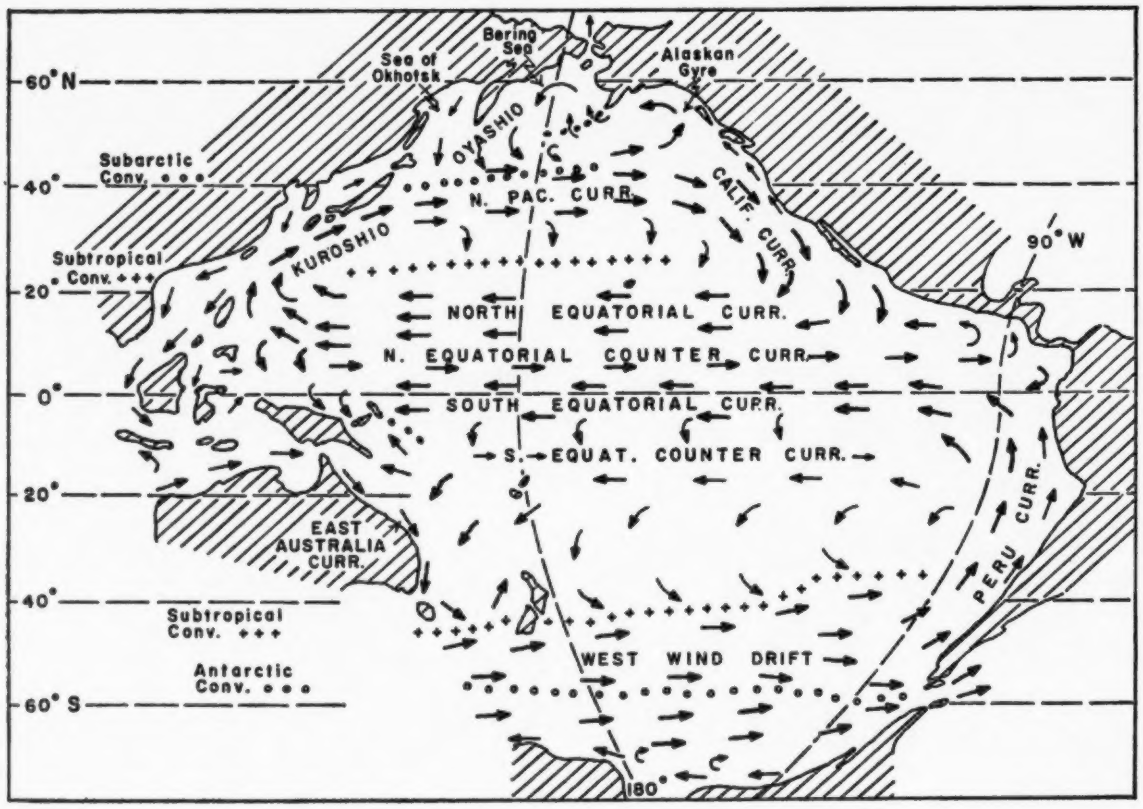
Bering Sea
Sea of Okhotsk
Alaskan Gyre
60° N
OYASHIO
Subarctic Conv. o o o
40°
N. PAC. CURR.
CALIF. CURR.
KUROSHIO
Subtropical Conv. + + +
90° W
20°
NORTH EQUATORIAL CURR.
N. EQUATORIAL COUNTER CURR.
0°
SOUTH EQUATORIAL CURR.
S. EQUAT. COUNTER CURR.
20°
EAST AUSTRALIA CURR.
PERU CURR.
40°
Subtropical Conv. + + +
WEST WIND DRIFT
Antarctic Conv. o o o
60° S
180°

Figure 6. Surface circulation of the Pacific Ocean. (From Geoge L. Pickard.)

However, the latest studies (L. V. Worthington, 1970) have confirmed accumulating evidence that points to the Norwegian Sea as the source of most of the deepest water in the North Atlantic. The relatively light water flowing into the Norwegian Sea is cooled by the atmosphere, becomes very dense, and sinks. Present indications are that some of this water spills out over the deepest part of the sill that extends between Scotland and Iceland and that it is principally this water that spreads southward along the bottom of the North Atlantic Ocean. In the south polar regions, the dense water that sinks from the surface of the Weddell Sea as a result of winter cooling and freezing supplies most of the bottom water that circulates in the depths of the South Atlantic, the Indian, and the Pacific Oceans. Another source of deep water is the Mediterranean Sea, though water that originates here does not sink all the way to the bottom.

Water flows into the Mediterranean through the Strait of Gibraltar, but it flows out again only beneath the surface. Because there is an excess of evaporation over precipitation in the Mediterranean, warm and salty water forms on the surface. Off the southern coast of Turkey, the salty surface water cools during the winter, sinks to intermediate depths, flows along the coast of Africa, and passes out into the Atlantic underneath the incoming water. Most of the warm, salty water that flows out of the Red Sea enters the Indian Ocean beneath the surface for similar reasons. However, it does not spread as far as the Mediterranean water, which can be traced far out into the deep waters of the North and South Atlantic and even around the Cape of Good Hope into the Indian Ocean.

As is the case in the Arctic, the Mediterranean is divided into two basins. A sill extending from Sicily to Africa rises to within 400 meters of the surface and separates the western basin from that on the east. A shallow sill is also present across the Strait of Gibraltar. Except as it circulates upward into the intermediate waters, the deepest water remains in the Mediterranean and does not flow into the Atlantic.

Bands of currents flowing alternately east and west parallel to the equator distinguish the surface circulation of the Pacific Ocean (Figure 6). Until recently it was thought that there were three currents as there are in the central Atlantic, the westward flowing North and South Equatorial Currents separated by an Equatorial Countercurrent flowing in the opposite direction. About 1960, however, a narrow, fairly weak countercurrent was identified in the South Pacific effectively dividing the South Equatorial Current in two. As a result, there are now five bands of currents recognized in the central Pacific and it has been necessary to assign new names. What used to be called the Equatorial Countercurrent is now named the North Equatorial Countercurrent. There is not yet a general agreement on how to name the currents situated on and south of the equator. Figure 2 illustrates one nomenclature in use and Figure 6 another.

Embedded in the current moving west along the equator is the Cromwell Current or Equatorial Undercurrent. It flows eastward 100 meters or less below the surface.

The North Equatorial Current defines the southern limit of the clockwise gyre in the North Pacific. Near the western side of the ocean, some of the water turns south and merges into the eastward North Equatorial Countercurrent and some turns north. This part continues northeast as the warm, intense Kuroshio Current. As it shifts to an eastward course beyond the coast of Japan it becomes known as the Kuroshio Extension. From the point where the Oyashio brings in water from the Bering Sea and the Sea of Okhotsk, the eastward flow is referred to as the North Pacific Current. This divides near the coast of North America and part of it continues south as the California Current, which eventually feeds back into the North Equatorial Current completing the gyre. The remainder of the North Pacific Current turns north to form a counterclockwise gyre flowing up along the coast of Alaska, through the Aleutian Islands into the Bering Sea, and back down towards the North Pacific Current as the Oyashio.

The South Equatorial Current forms the northern portion of the South Pacific gyre. Continuing counterclockwise, the East Australia Current flows south along the western boundary of the ocean. It carries less water and is not as well defined as the western boundary currents in the other oceans, however. The West Wind Drift or Antarctic Circumpolar

Current continues the gyre, and part of it passes up the coast of South America as the Peru or Humbolt Current. This turns west close to the equator flowing into the Equatorial or South Equatorial Current.

The Peru Current is typical of eastern boundary currents. It is a broad, slow current carrying cool, less saline waters towards the equator. In sharp contrast, the western boundary currents, typified by the swiftly flowing, concentrated Kuroshio, Florida Current, and Gulf Stream, carry warm, salty water towards the poles. The Peru Current is associated with southerly winds blowing towards the equator parallel to the coasts of Chile and Peru. Since the direction of net transport by the wind is 90° to the left of the wind in the southern hemisphere, the warmer surface waters move out to sea directly away from the coast and cooler waters from a depth of a few hundred meters or less rise to take their place. This condition is known as upwelling and it occurs on the eastern boundaries of oceans where the prevailing wind blows towards the equator along the western margins of continents, notably off the coasts of Peru, California, and southwestern Africa. In these places, essential plant nutrients which would otherwise sink to the bottom are continually being brought to the surface. The upper waters are rich in plankton as a result and the sea teems with fish, which depend upon the plankton for their food, though the benefit is indirect in the case of the larger fish because they usually eat the smaller fish and not the tiny plankton themselves. A fuller discussion of the biological significance of upwelling is given in Chapters 9 and 10.

The Indian Ocean is different from the Atlantic and the Pacific in that most of it lies south of the equator. Although there is no northern gyre, the counterclockwise gyre typical of the southern half of the other oceans also develops in the surface water of the South Indian Ocean (Figure 7). It is bounded on the north by the South Equatorial Current and on the south by the West Wind Drift. The western boundary current, called the Agulhas, is characteristically intense and well defined during the months from November through March, but its flow is modified by the situation in the equatorial region of the Indian Ocean during the other months of the year.

From November through March, the pattern of surface circulation near the equator is similar to that in the Atlantic, with a North Equatorial Current and a South Equatorial Current flowing westward separated by an Equatorial Countercurrent flowing eastward. In April, however, the time when the prevailing northeasterly trade winds north of the equator die down and the southwesterly monsoon winds begin to blow instead, the North Equatorial Current reverses direction and the Monsoon Current flows eastward in its place (Figure 7). From May through September, the Agulhas subsides and the swiftly flowing Somali Current, which moves northward along the African coast, develops and becomes the dominant current on the west.

Measuring Currents

Many kinds of data have been pieced together from many sources to create the picture of ocean circulation as it is presently understood. Most of the information we have on surface currents has been gathered from records that navigators have entered in ships' logs over the years. By calculating the drift of a vessel away from the course it was steering, experienced seaman could compute the speed and direction of a current fairly accurately. This information continues to be collected and it is supplemented with data obtained from instruments specifically designed for the purpose and with data gathered by other, indirect, oceanographic techniques.

Though there is a great variety of instruments, there are essentially only two methods of measuring currents directly. One, the Lagrangion, involves following the path of an instrument as it drifts through the water. Usually the drift or float sends out radio or sound signals or it is tracked by radar. The speed and direction of the current are recorded aboard the ship or at a nearby shore station. Sometimes simple drift bottles are set afloat at one point and recovered after a time wherever they wash ashore. A self addressed postcard is the only tracking mechanism. One is inserted in each bottle with instructions requesting the

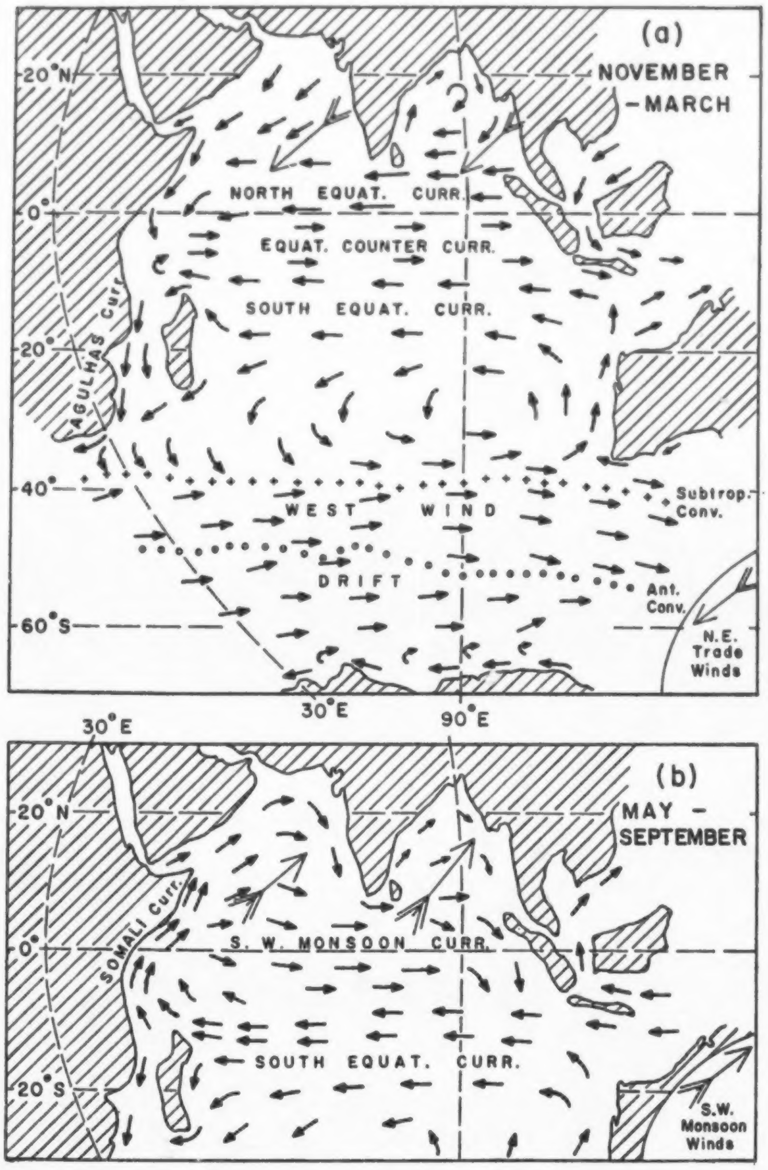
(a)
NOVEMBER
-MARCH
20°N
0°
20°
40°
60°S
NORTH EQUAT. CURR.
EQUAT. COUNTER CURR.
SOUTH EQUAT. CURR.
AGULHAS Curr.
WEST WIND
DRIFT
Subtrop. Conv.
Ant. Conv.
N.E. Trade Winds
30°E
30°E
90°E
(b)
MAY -
SEPTEMBER
20°N
0°
20°S
SOMALI Curr.
S. W. MONSOON CURR.
SOUTH EQUAT. CURR.
S.W. Monsoon Winds

Figure 7. Surface circulation of the Indian Ocean.
(From George L. Pickard.)

person who finds it to write the place and time of recovery on the card and to mail it back to the "sender." A great deal of information can be gathered in this way because it is easy to set great numbers of bottles adrift. The data collected are primarily useful in inferring patterns of surface circulation over the continental shelves.

Recently, with the development of a neutrally buoyant float named after its inventor, John Swallow, it has become possible to measure deep water movements by the Lagrangian method. The Swallow float, originially made of aluminum tubing, is now made of a hollow glass sphere. Since these materials are less compressible than water, the instrument can be ballasted so that it will hover at any preselected depth beneath the surface. It emits a little beep at regular intervals and the sound is picked up on shipboard through hydrophones. In this way, its path and speed are recorded by direct measurement.

It is also possible to trace the path of a current by making chemical or physical analyses of water samples that have been collected after certain contaminants and dyes have been released into the water. It is, however, necessary that the material be relatively easy to detect even when it becomes tremendously diluted.

The other method of measuring currents directly, the Eulerian, involves placing an instrument in the water at a fixed point and measuring the speed and direction of the water that flows past it. A series of such measurements will reveal the total path of the current. These instruments vary greatly in complexity. The simplest of them are the drags and drogues. These are metal or wooden crosses, fish nets, or parachutes suspended from a moored buoy or ship by a fine piano wire or nylon filament. The current exerts a force against the instrument which pulls the wire out at an angle in a particular direction. The speed of the current is calculated by a simple formula relating the size and weight of the instrument and the angle of the wire.

The more complicated current meters come in various designs. Most of them contain a propellor or screw which is turned by the water. Speed is determined by any of a number of techniques for counting the number of revolutions in a given period of time, and direction is derived by various means from a magnetic compass. The classic example of the the type is the Ekman Current meter. This reliable mechanical device was developed over fifty years ago by V. W. Ekman and it has been replaced only as instruments with more efficient means of transmitting the data have been designed. In Ekman's design, the propellor works some small gears which record the number of revolutions on a dial. In addition, at timed intervals some small bronze balls drop into a slightly inclined channel affixed along the top of the magnetic compass needle. They roll down and collect in one of thirty-six compartments evenly arranged in a circle beneath the compass, and the general direction of the current during the time of measurment aan be deduced by counting the number of balls in each compartment. If the groups of balls are marked so that they can be distinguished from one another, a measure of how the current shifts can also be obtained. The Ekman current meter is usually lowered from a moored ship, and it must be retrieved in order to collect the data. Current meters of more recent design are usually mounted on or suspended from moored buoys, and the information is transmitted to a ship or shore station by electrical cables or radio signals.

Currents can also be measured by determining the rate at which an electrically heated wire cools when it is lowered to a fixed position in the water. In practice, the wire is maintained at a constant temperature by automatically adjusting the current so that the rate of heating balanced the rate of loss to the water. The magnitude of the electric current is then a measure of the speed of the water. This instrument, called the hot wire anemometer, does not measure the direction of ocean currents.

It is possible to measure both the speed and the direction of currents by indirect methods. An electrical current is induced in sea water as it moves through the earth's magnetic field. By measuring the magnitude and direction of the electrical current, a measure of the speed and direction of the water's current is obtained. An instrument that does this was developed by William S. von Arx and it is called the GEK, short for geomagnetic electrokinetograph. The design and functioning of the GEK, as well as those of the other instruments mentioned in this article, are described clearly and in more detail by Pickard and von Arx in the references listed.

Most of our knowledge of circulation deep in the ocean has come indirectly from studying the distribution of physical properties. As described in Chapter 4, seawater samples are collected from various depths at a known position or oceanographic station, their temperature and salinity are measured, and, from those, their density is calculated. From information about density distribution and pressure gradients gathered in this way, oceanographers are able to predict the speed and direction of water movements. This technique, which is used to deduce patterns of circulation theoretically, is called the geostrophic method.

No matter what instrument of method is used, one of the biggest obstacles to obtaining accurate current measurements is the difficulty of determining a precise position at sea. For work with currents near the shore, the measuring devices can be positioned exactly on oil-drilling platforms or other stable structures. For work carried on farther out to sea, modern systems of radio and satellite navigation have greatly increased the accuracy of measurements, but these systems do not reach to all parts of the ocean. Even when the ship has been positioned with the greatest precision possible, it will not stay there, and this makes it especially difficult to track the path of a drifting instrument continuously. Not only must the instrument be tracked, but the drift of the ship must also be calculated. Since a buoy can be moored more securely than a ship against the effects of wind and current, it is customary to fix the ship's position by maintaining constant radar contact with an anchored buoy. Even the buoy will shift, however, and its position with respect to the bottom must be checked by taking soundings from time to time. As is the case with other oceanographic measurements, accuracy in measuring currents depends to a large extent on the precision with which it is possible to navigate.

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7. AIR-SEA INTERACTION

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In this section we shall be concerned with the ways the ocean and the atmosphere exchange heat, moisture, gases and salts. Currents and waves are also appropriate topics under this title, but for convenience they are considered elsewhere (see Chapters 5 and 6).

1. Heat Balance of Planet Earth

Year by year the entire surface and gaseous atmosphere of the planet Earth radiate to space the entire energy they receive from the sun during the same period. This we know because our climate shows only small fluctuations. Careful calculations based on world-wide observations of temperature, moisture, and cloudiness show that within 40° of the equator, the earth and atmosphere receive more radiant energy than they give back to space; and, conversely within 40° of the poles, outgoing radiation exceeds incoming radiation. The fluid portions of the globe, the oceans and the atmosphere, complete the heat balance, carrying heat to high latitudes and bringing cooling to low latitudes, thereby tempering the climate of both.

The winds of the atmosphere rather than ocean currents transport the lion's share of this heat, nevertheless the ocean plays an important role in maintaining the earth's climate as we know it. Since the atmosphere is quite transparent to solar radiation, the main cycle of heat energy within the earth and its atmosphere is as follows: from the sun to the earth's surface (of which 70% is ocean); from the earth's surface to the atmosphere; and, after some redistribution, from the atmosphere to space. The way heat is exchanged across the ocean surface is thus one link in the chain of processes which determines the climate.

2. Heat Exchange at the Ocean Surface

Three processes are involved in the flow of heat between ocean and atmosphere and the most important of these is radiation. During the day solar energy, at both visible and infrared wavelengths, reaches the ocean surface in an amount which depends on latitude, season, and cloudiness. In middle latitudes the daily totals range, on clear days, from 600 cals/cm^2 in midsummer to 100 cals/cm^2 in midwinter, with values smaller by a factor of 5 on heavily overcast days.* The earth's surface also gives rise to a stream of radiant energy, as does any body above absolute zero of temperature, but even when skies are cloudless most of this invisible, infrared radiation is absorbed in the atmosphere. The active absorbers are carbon dioxide and water vapor, and since by Kirchoff's law a good absorber is also a good radiator, the atmosphere radiates back to the surface *almost* as much energy as the surface radiates to the atmosphere. The net loss from the surface in this manner is about 100-150 cals/cm^2 per day under cloudless skies and smaller by a factor of ten under an overcast sky.

The second process by which the ocean and the atmosphere exchange heat is through the evaporation of water. When 1 gram of water evaproates into the atmosphere, 600 calories of heat are removed from the ocean. When the water vapor condenses and is returned to the surface as rain or snow, this heat is made available to the atmosphere. Reckoning the annual average evaporation from the ocean as 3 mm per day (or 0.3 gm/cm^2), this implies a heat exchange of 180 cals/cm^2 per day from ocean to atmosphere. Evaporation is very variable, generally increasing with both water temperature and wind speed and decreasing with increasing latitude. In hurricane force winds the heat associated with evaoproation has been computed as 1000 cals/cm^2/day.

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*1000 cals/cm^2 will heat 10 m of water by 1°C.

The third way in which the ocean and the atmosphere exchange heat results from the direct flow of heat between warm and cold parts of a solid or fluid. When cold air moves over warm water, heat flows from the ocean to the atmosphere; when warm air flows over cold water, the heat flows from the atmosphere to the ocean. Direct heat transfer increases with both wind speed and with the difference between water and air temperatures; like evaporative heat, it is highly variable. In tropical regions it is generally small, about 1/10th of the heat of evaporation, but in high latitudes it is often as large as the evaporative heat flow.

Direct and evaporative heat flow are evaluated using a mixture of theoretical ideas and empiricism and they have yet to be carefully evaluated. Radiative heat flow is based on measurements made along the fringes of the oceans and interpolated to great distances. Despite these uncertainties, the general inferences to be drawn from heat balance estimates appear accurate.

a. Annual heat balance

If the three processes by which heat flows across the ocean surface are averaged for the entire year and are then added (with proper regard to sign), we obtain the annual heat balance of the oceans (see Figure 1). Within 30° of the equator, radiative heat input exceeds evaporative and direct heat loss and the oceans gain heat; within 30° of the poles the heat losses exceed radiative input and the oceans lose heat. The connection between the annual heat balance and the annual mean temperature of the oceans is also shown in Figure 1. Since the mean temperature of any latitude does not change from year to year, oceanic circulation must transfer the heat surplus from low to high latitudes, warm water moving towards the poles and cool water towards the equator (see Chapter 6).

b. Seasonal heat balance

We shall briefly mention the relation of seasonal variation in heat balance to seasonal variation in surface temperature. In the northern hemisphere from February-March until August-September, on the average, incoming radiation exceeds all heat losses to the atmosphere and the ocean warms up. During the remaining half-year the converse is true and the ocean cools. In Figure 2, I have shown the seasonal variation in ocean temperature measured at Woods Hole, Massachusetts, and have indicated schematically the net heat balance.

c. Short-term variations

An examination of the daily values from which the smooth curve of Figure 2 was drawn shows short-term reversals of the seasonal variation in surface temperature. Daily values for 10-day periods in both July and December, 1968 show this effect (underlined values). Surface temperatures, $^{\circ}$C, for the warming period are: 17.8, 18.6, 19.2, 19.4, 19.2, 18.6, 19.3, 19.7, 20.0, 20.2. For the cooling period they are: 7.5, 6.7, 6.1, 5.8, 5.0, 3.6, 4.2, 4.5, 3.0, 2.4. The changes at a mid-ocean station are similar if somewhat less violent. Periods of storms with clouds and strong, cold winds cause large heat losses, but these stormy periods are interspersed with calmer periods when the oceans warm. Our knowledge of these short-term variations in heat balance is still rudimentary.

3. The Water Balance of the Oceans

Without the presence of oceans and water vapor in the earth's atmosphere, the earth's climate would be more extreme than it is. Many meteorologists believe that the central problem of their science is to understand and predict the occurence, movement, and condensation of water vapor in the earth's atmosphere. Part of this problem involves the movement of water across the ocean surface.

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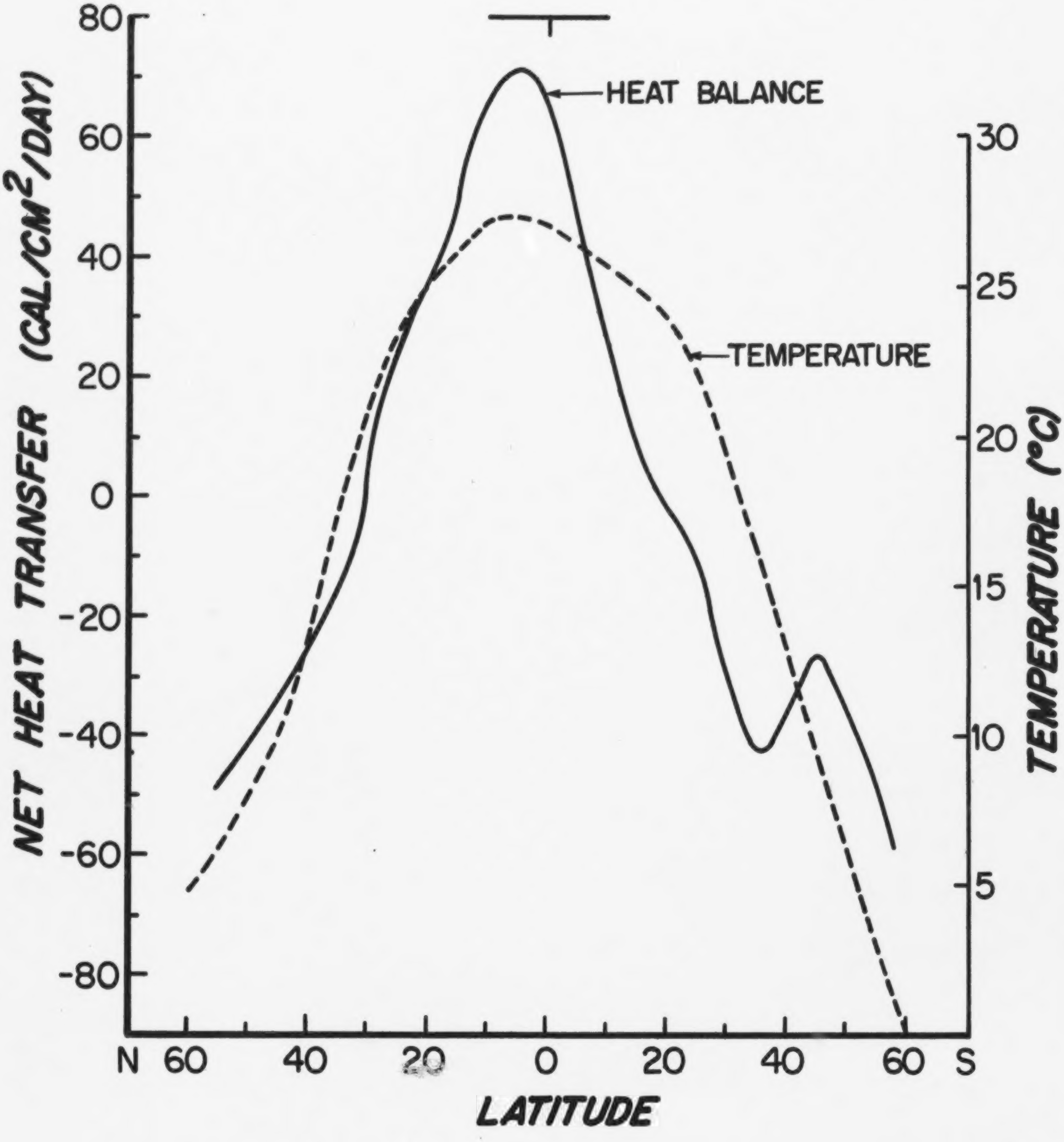

Figure 1. (Solid curve) Heat flow through surface of the ocean as a function of latitude--annual average value; heat gain is reckoned positive. (Broken curve) The temperature of ocean surface as a function of latitude--annual average.

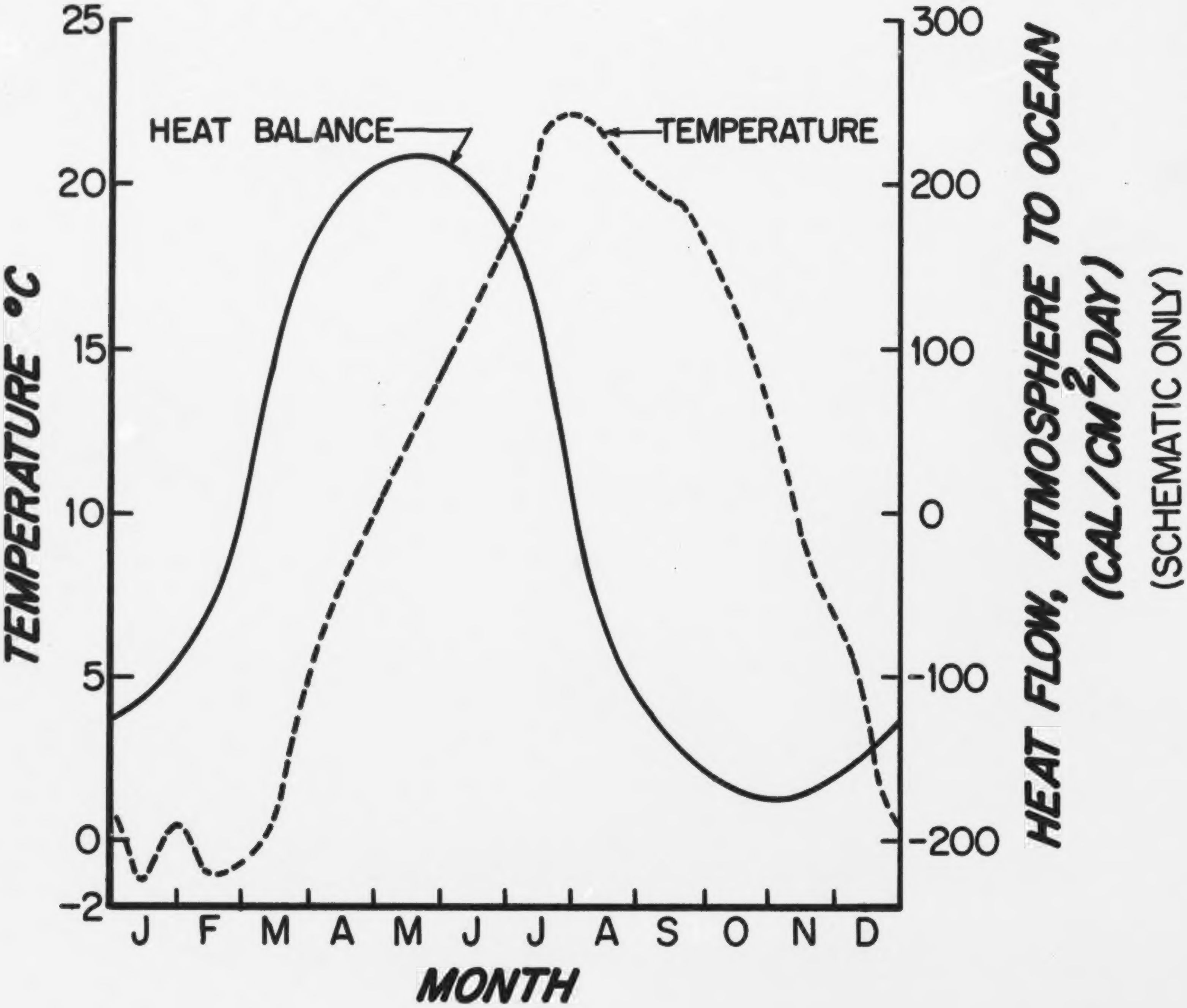

Figure 2. (Broken curve) The temperature of the ocean at Woods Hole, Massachusetts, during 1968--10-day averages.
(Solid curve) The corresponding heat flow through the surface (schematic).

Over the oceans, evaporation averages about 110 cm/year, and this same amount is returned by precipitation on the oceans and run-off from the continents. River discharge from the world's land masses is estimated as the equivalent of 10 cm/year: thus oceanic precipitation must average 100 cm/year. (Measurements of rainfall made on a ship are found to be sensitive to the exposure of the rain gauge and are deemed unreliable). Since the ratio of ocean area to land area is 2.4 to 1, the annual run-off is equivalent to a precipitation overland of 24 cm/year; this amount is 1/3 of the land's measured average annual rainfall of 70 cm/year. Evidently the remaining 2/3 of the land's rainfall must reevaporate into the atmosphere.

On an annual average, evaporation exceeds precipitation in subtropical regions and surface waters are saline there, see Figure 3. In high latitudes, precipitation exceeds evaporation and surface waters are relatively fresh. Since surface salinities are observed not to change from year to year, the same ocean currents carrying warm water towards the poles to balance the oceanic heat budget must also carry salt, whilst the cold currents carry fresher water towards the equator.

4. Exchange of Gases

Gases which are present in the atmosphere are also present in the ocean since they are constantly exchanged across the ocean surface principally by molecular diffusion. Oxygen and carbon dioxide are the most important because they are vital to life in the ocean. The amount of oxygen dissolved in the ocean, like most other of the constituent gases, is only a fraction of that in the entire atmosphere, but the total carbon dioxide content of the oceans, including that weakly locked up in dissolved carbonates and bicarbonates, is 60 times the content of the atmosphere. Clearly there is a massive reservoir of carbon dioxide in the ocean.

Since the industrial revolution, large quantities of carbon dioxide have been added to the earth's atmosphere by the combustion of coal, gas, and oil (amounting to an increase of about 15% in the last 50 years). How much has been retained in the atmosphere and now much has entered the ocean? There is a lively unsettled scientific controversy concerning this question because carbon dioxide in the atmosphere is an active radiating gas and a substantial increase would upset the radiation balance of both the earth's atmosphere and its oceans and lead to a change in climate.

5. Wave Breaking and Bubble Bursting

When the wind reaches speeds of about 7 knots, a few waves begin to break and whitecaps form. A whitecap is a region where air is entrapped by a falling wave crest and takes the form of numerous tiny air bubbles which range in size from a fraction of a millimeter up to several millimeters in diameter. Most of these bubbles rise to the surface and break, and high speed photography has shown (see Figure 4) how drops of seawater are then thrown several centimeters into the air. Many fall back to the ocean, but some are carried aloft by the turbulent winds and slowly evaporate leaving behind a semicrystalline mass of sodium chloride. Over the ocean and to a lesser extend the bordering land masses, this salt is found in the lowest few thousand feet of the atmosphere, and although its mass is only about 1/10,000,000 part of the mass of water vapor, nevertheless the salt plays a vital role in the steps by which the water vapor condenses and returns to the ocean.*

Condensation of water vapor without excessive supersaturation requires the presence of solid surfaces. Any small dust particle will serve, but those, like a salt nucleus, with an affinity for water are preferred. The favored drops attain a larger size than their fellows, settle through them, collect them and fall out as rain. The presence of numerous salt particles over the ocean and fewer over the continent is one factor that leads to smaller rainfall over land (70cm) than over the oceans (100cm).

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*Drops formed by bursting bubbles also carry a positive charge to the atmosphere, and this too may influence the subsequent formation of rain.

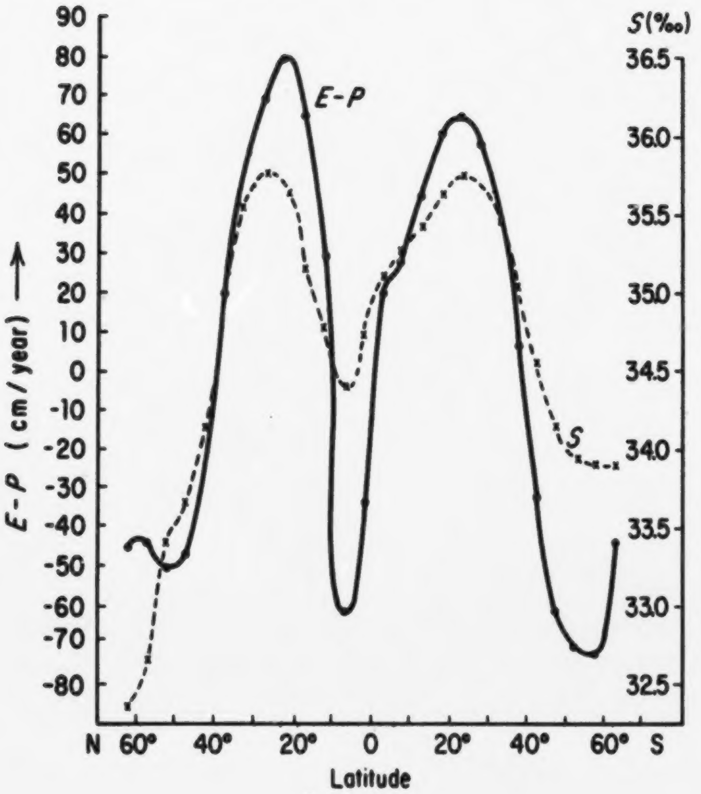

Figure 3. (Solid curve) The difference between evaporation of water from the ocean and precipitation on it as a function of latitude--annual average.
(Broken curve) The salinity of the surface water as a function of latitude.

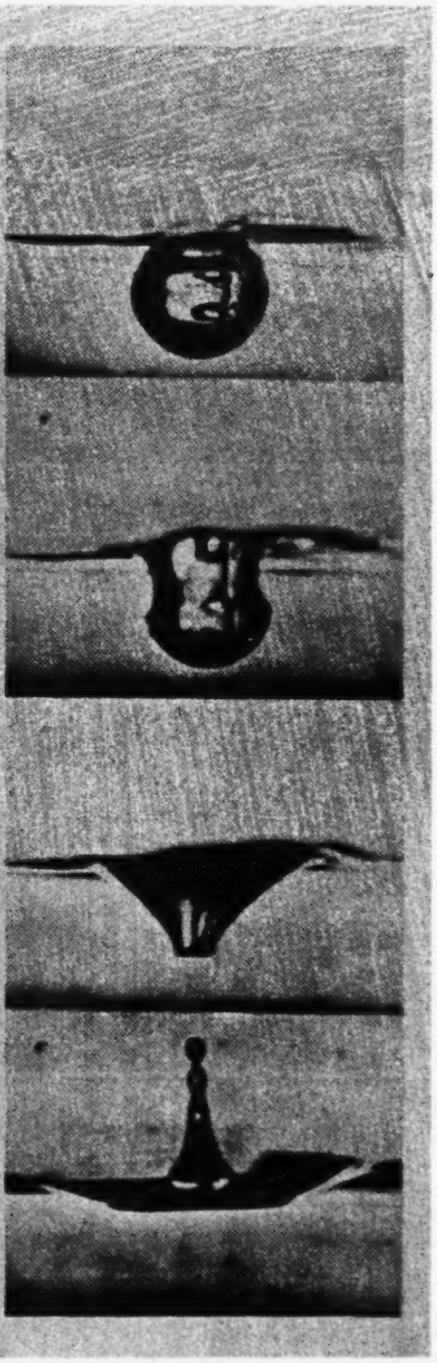

PLATE VII. Birth of bubble jet is shown in four stages (top to bottom). Bubble measured 1.7 mm in diameter. Total elapsed time was 0.0023 second.

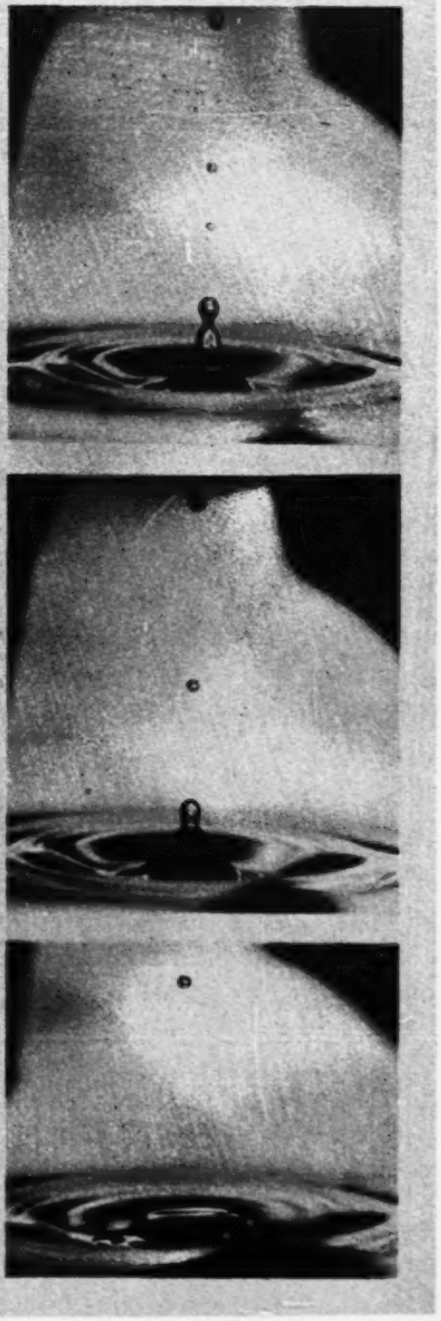

PLATE VIII. Life of bubble jet is shown in three stages (top to bottom). At top three jet drops are visible above fully formed jet. In center jet is collapsing. At bottom collapse is nearly complete, one drop still visible. Bubble producing jet was 1 mm in diameter. (Photos by Charles Kientzler)

Figure 4. High speed photographs of an air bubble bursting at a water surface and throwing drops into the air above.

6. Hurricanes

Extremes of air-sea interaction occur in the presence of the small intense tropical circulations called variously hurricanes (in the Atlantic), typhoons (in the Pacific), and cyclones (in the Indian Ocean). These circular storms arise only in oceanic regions and, in the northern hemisphere, have winds which at low levels blow counterclockwise and inwards, but at high levels (above 30,000 ft.) blow clockwise and outwards (see Figure 5).

In the central core of the storm or "eye," weak winds accompany low surface pressures (900-950 millibars) over a diameter of about 20 miles. Beyond 20 miles from the center, the surface winds may be 100 knots, remaining in excess of 65 knots, or hurricane force, out to between 50 to 200 miles. At greater distances the winds are less and the effects of the storm are generally felt only as far as 300 to 400 miles from its center. Commonly this figure is smaller and rarely larger.

The warm moist air circulating in the lower levels of the storm converges in a spiral path along rain bands and in a central region peripheral to the eye it ascends, flowing out at high levels. The region of ascent is marked by very heavy rainfall, up to 20-30 cm/day. The contrast between this violent wind and heavy rain area and the quiet almost cloud free eye is the most celebrated feature of these storms.

Tropical storms are generally formed within 5 to 15 degrees of latitude on either side of the equator, but all of them subsequently follow paths that carry them towards the poles. At first, Atlantic hurricanes generally travel westward into or near the Caribbean island chain before curving north and then northeastward. When they move over cold water or land areas, they weaken rapidly because their source of warm moist air is no longer present.

The greatest hazard associated with hurricanes, in respect of loss of life and property damage, is not generally due to wind or rain but to the catastrophic flooding which occurs as the hurricane crosses the shore.

7. Methods Employed in Investigating Air-Sea Interaction

We give here an outline of techniques used in observing the heat and moisture flow between the ocean and atmosphere and those used in measuring the temperature and salinity of the upper ocean, which are the physical properties influenced by these flows. The role of human inventiveness and imaginative thought in these investigations should not pass entirely unmentioned.

a. Temperature

Measurements of the geographical distribution of temperature and its variation with time are made from (1) buoys, which record or broadcast data, (2) ships--commercial and military, weather ships and research vessels, (3) aircraft--weather reconnaissance and research, and (4) satellites. For observation of temperature, mercurial thermometers, thermomographs, and (electrical) resistance thermometers are widely used. Recently, aircraft and satellites have used remote instruments called radiometers, which are ultra-sensitive heat detectors. This last instrument, though a powerful new tool, gives information only about the skin of the ocean, whilst the others can be lowered from ships or suspended below buoys to measure the vertical variation in ocean temperature.

b. Salinity

Salinity is not so widely measured as temperature. By capturing a volume of sea water, "water catching," and making a careful chemical analysis, salinity can be determined. A modern method measures the electrical resistance of the sea water in the ocean and, provided temperature is also measured, salinity can be deduced (see Chapter 4). Salinity measurements, because they require specialized equipment, are mostly restricted to military and research vessels and buoys. To date no technique has been found practicable for the remote measurement of salinity.

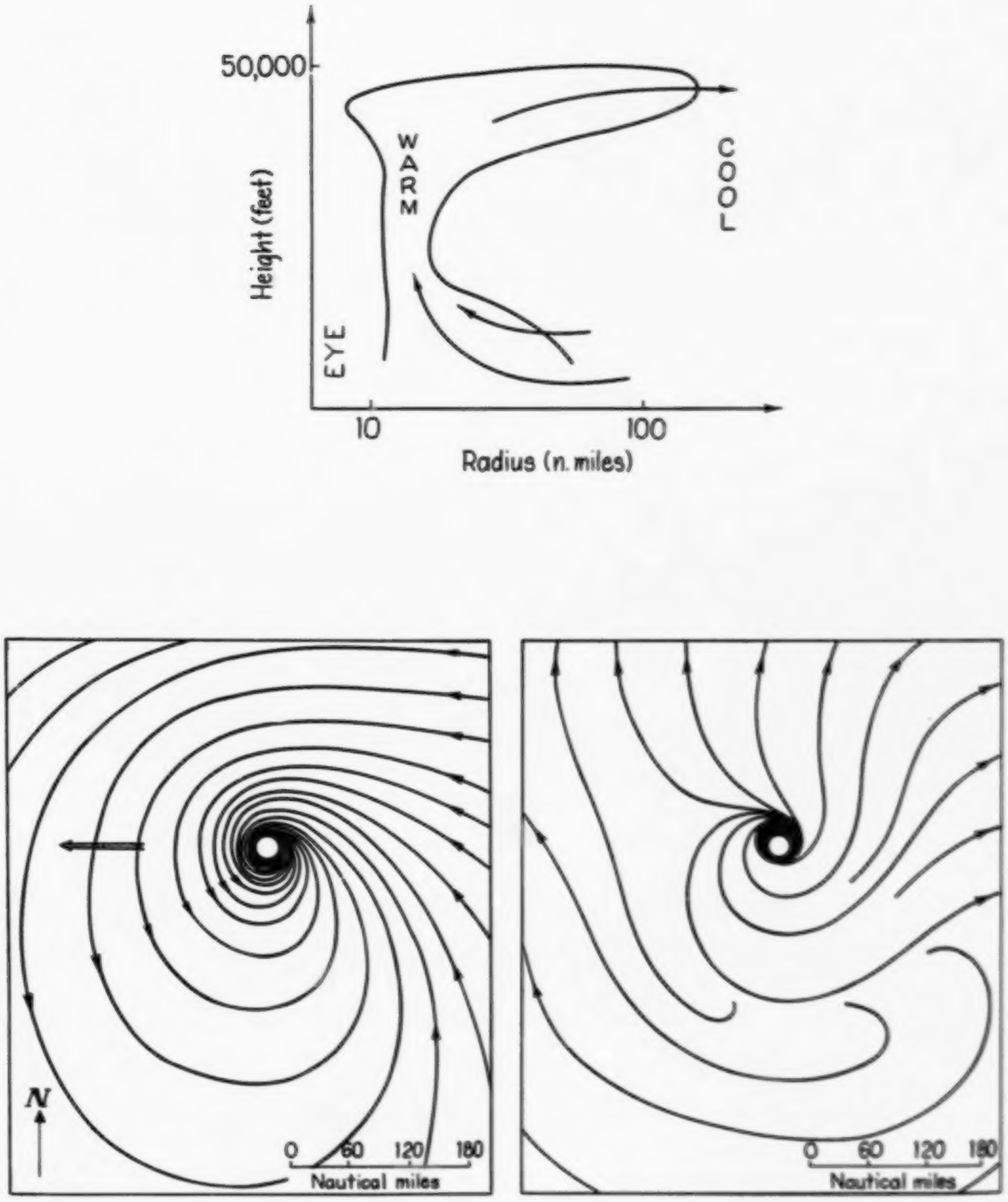
50,000
Height (feet)
WARM
COOL
EYE
10
100
Radius (n. miles)
N
0 60 120 180
Nautical miles
0 60 120 180
Nautical miles

Figure 5. The circulation of a northern hemisphere hurricane. Lower left shows the motion of the air at 1000 ft; lower right shows the air motion at 45,000 ft. Both are viewed from above. Upper diagram shows air entering heavy rain area at low levels and leaving aloft.

c. Moisture and heat flow

Estimates of direct and evaporative heat flow, and hence also evaporation, are made from standard meteorological observations at sea; namely sea and air temperature, hunidity, and wind measured from ships and buoys. Direct observations require sensitive anemometers, thermometers, etc., mounted on stabilized buoys or texas towers, and much expertise; a few research groups around the world are involved in such programs.

Radiative heat flows, both that from the sun and that lost from the surface, are measured with heat sensitive instruments. As we remarked earlier, almost all these observations are made from continental stations by Westher Services, although some island stations and research ship and aircraft observations improve the picture. Satellites, by measuring relfected sunlight and the thermal radiation flow from the planet (outside the earth's atmosphere), will, it is hoped, provide means of estimating the corresponding radiative flows at the earth's surface.

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8. SEA ICE

by William G. Metcalf

Woods Hole Oceanographic Institution

Forward

The following is not intended to be a 30-45 minute lecture on sea ice for high school students. Rather, it is designed to present material on the subject from which a 30-45 minute lecture can be drawn. Just how much of it the teacher will wish to incorporate will depend upon the teacher's assessment of the ability of the class to handle the material. This naturally will vary from group to group.

Actually, most of the material on ice is simply descriptive. From the chemical and physical standpoint, the fascinating aspect of water and ice lies in the remarkable changes in density with changes of temperature and changes of state. If the students have a sufficient background - for example, a senior class with a background in chemistry and/or physics - then possibly they will be able to appreciate the very unusual ways in which water and ice behave. The behavior of water when it undergoes a change of state from liquid to solid or vice versa is quite different from that of most common substances on earth and is, to a very great extent, responsible for the environment as we know it.

As many students know, most substances become more dense as they cool. Some students will know that water is peculiar in that although it becomes denser as it cools through most of the temperature range at which it is liquid, it reaches a maximum density at about 4°C. As it cools below this point, it expands, thus becoming less dense. At 0°C, where pure water freezes, it undergoes a great expansion as it changes into the solid state. This has a most important effect upon our environment. Most substances become denser as they cool, and this proceeds right through the point at which they change from the liquid to the solid state. Solidified steel, for example, sinks in molten steel.

Have the students speculate as to what the world would be like if ice sank instead of floated on water. For example, if ice were denser than water, it would sink to the bottom of streams, lakes and the ocean. There it would be protected from the thawing by the sun's rays and would be very slow to melt. Soon all the bodies of water would fill with ice from the bottom up. Only the top bit would melt, and melt water would flood the surrounding land which would be completely uninhabitable. A vast glacial age would take over. The fact that ice floats instead of sinks is one of the most important features of our environment.

Another very important thing about water is its very high specific heat. It takes approximately 1 calorie of heat to raise a gram of water 1°C. This is appreciably more heat than is required to raise a gram of most other common substances an equal amount. Similarly, when a gram of water cools by a degree, a calorie of heat is released to the environment. Because of the great amount of heat required to change the temperature of water, we have a very even climate. Unlike the moon which is terribly hot on the light side and terribly cold on the dark side, the earth changes temperature only slightly between day and night. Some of this is the so-called "greenhouse effect" of the atmosphere, but much of it is due to the slowness with which water cools off with the loss of heat and the slowness with which it heats up with the application of heat. In fact, much of the "greenhouse effect" is due to the high specific heat of the water vapor in the atmosphere.

Another very important and remarkable thing about water is its very high heat of fusion. As was stated above, it requires 1 calorie of heat to raise a gram of water 1 degree C. However, it requires nearly 80 calories to change a gram of ice at 0°C into water of exactly the same temperature. This is an extraordinarily high figure compared with other common substances on earth, and it is the reason why ice caps in the high latitudes do not change from ice to water each summer and back to ice the following winter with a resulting change of sea level each season of untold meters which in turn would make living near the seacoast out of the question.

In other words, the high heat of fusion, like the high specific heat, has a very moderating effect upon the climate and is one of the reasons why the earth's climate is equable enough to support life as we know it.

* * * * * * *

It is not expected that all teachers will wish to attempt to explain all this to each class. However, if the teacher can have some of these principles in mind and can pass on a rough outline of them to the students, it may awaken the students' interest and appreciation of the truly astonishing properties of water and ice, and this may make them more receptive to the material in this chapter on Sea Ice.

By the way, it should be mentioned that fresh water and salt water differ in various ways. Their specific heats and heats of fusion, though differing slightly, do not make any material difference in their ameliorating effect upon the climate. One thing should be mentioned, however. As was stated above, fresh water reaches its maximum density at about 4°C. With the addition of salt, the freezing point is lowered somewhat, and the temperature at which the water reaches its maximum density is lowered at a slightly faster rate. At a salinity of about 25°/oo, the freezing point and the point of maximum density coincide, and this situation prevails at higher salinities. That is, the water reaches its greatest density just at its freezing point. Then as it freezes, it becomes suddenly less dense.

For further information about water, ice, heat of fusion and specific heat, the teacher might wish to refer to the Handbook of Chemistry and Physics, published by the Chemical Rubber Publishing Company. It contains tables showing these characteristics of water and many other substances. The Encyclopedia Britannica also contains interesting information on these matters.

Having unburdened myself of the foregoing, I shall now get a little closer to the subject of Sea Ice.

Sea Ice

The freeaing point of water is affected by the salinity. Whereas pure water freezes at 0°C (32°F), salt water freezes at a somewhat lower temperature. Sea water of about 35°/oo salinity, which is a reasonable figure for surface water in the open ocean, freezes at about -1.9°C (28.5°F). When freezing starts, a loose accumulation of separate ice crystals forms at the surface. Under calm conditions, these give the appearance from the distance of a slick, but under rougher conditions, this formation may go unnoticed. In fresh water, early freezing may take the form of thin, clear, brittle glass-like sheets of ice at the surface in calm weather. Ice of this sort is frequently found in the Arctic where melt water or surface run-off commonly reduces the surface salinity so much that the water is practically fresh.

With continued cooling of salt water, the loose crystals begin to bind together to form a white opaque slush. As consolidation proceeds, the ordinary motion of the sea surface keeps the ice broken into small pieces which, in the course of colliding with each other, develop into pancake-like structures a foot or two across with slightly raised edges. The formation of pancake ice is sufficient to reduce the waves so that even in windy conditions, the sea surface takes on a smooth undulating appearance.

Rough weather may retard the freezing process because the turbulence, bringing water up from below, produces a large reservoir of heat to be dissipated before freezing can proceed.

From the pancake stage, the ice gradually increases in thickness and in horizontal dimensions. Simultaneously, the ice, which was soft and had little tensile strangth at the start, becomes harder and stronger.

Actually, as freezing begins, it is only fresh water ice crystals which form, and the salt is left behind in solution. This brine solution, being relatively dense, slowly sinks below the surface and mixes with the water beneath the ice. Under common Arctic conditions water with a salinity of 35°/oo may form ice which has a salinity of 3.5°/oo, the salt being present in brine cells entrapped in the midst of pure ice crystals. With continued freezing, more and more pure ice separates out, and the brine left behind becomes more and more concentrated. Under the very coldest conditions, the brine may become so concentrated that various crystalline salts precipitate. Under very rapid freezing conditions, much brine is entrapped among the ice crystals; under slower freezing conditions, most of the brine escapes. Thus it is not possible to say just how salty a given piece of ice can be expected to be - it depends upon the conditions under which it was formed.

In cases of unusually rapid freezing, as when a lead (a large opening in the ice pack) is formed by the wind and currents in the midst of a very cold period, a major part of the brine may be prevented from escaping. As more and more fresh ice crystals form and the remaining brine becomes more and more concentrated, the brine may be subjected to considerable pressure due to the fact that the ice crystals represent a considerable expansion over the size of the original water. It often happens that this pressure forces the brine out through small pores or cracks onto the surface of the ice. In mid-winter, newly frozen leads frequently have "salt flowers" formed - crystalline salt formations "growing," as it were, on the surface.

But to get back to the freezing season - as consolidation continues, vast areas of the ocean become more or less solidly covered with ice floes which may range in size from a few meters to many kilometers across. Well within the Arctic pack, the wave action of the open ocean is lost, but near the edges, the constant motion from the unfrozen areas keeps the floes from becoming very large. The undulation due to the influence of the open ocean can be felt several miles within the pack, and it is probably a limiting factor in determining floe size even further from the edge of the pack.

Inasmuch as ice is a fairly efficient insulator, especially when covered with snow, it sharply reduces the loss of heat from the water below. It is uncommon for ice of greater than 2.5 to 3 meters in thickness (8-10 feet) to form under usual conditions in a single freezing season.

Throughout much of the central Arctic Ocean, ice will last through the summer and become thicker the following winter. Over successive winters, the ice will build up to greater thickness, but more than 5 meters (16 feet) is not usually found in nature. Another factor is involved in ice thickness, however. Ice floes are constantly moving about in response to the forces of winds and currents and are constantly encountering obstacles such as land masses or other large floes. These other floes may be affected by different winds or currents, and in the resulting collisions, floes override each other - a phenomenon called "rafting." Gigantic ridges of ice may be pushed up by the pressure of opposing floes. In some cases, the ice may be forced up as much as 15 meters (50 feet) above the surrounding pack. It follows that the ice is also forced well below the surface beneath the pressure ridges.

Throughout the freezing season, motion in the pack causes cracks and leads to form. These refreeze quickly. When a lead opens up in one area, it probably means that rafting and pressure ridge formation is taking place in an adjoining region. Even at the height of the freezing season, there are always cracks and leads present in the Arctic Ocean, but floes with diameters of many kilometers are common.

The drift of the ice is governed by a combination of forces such as winds, currents, and obstructions. In theory, the ice drifts to the right of the wind direction in the northern hemisphere, and if the pack is not overly consolidated this has frequently been observed. However, in more consolidated pack ice, the obstructions of distant land masses or of floes from adjoining areas where the winds and currents may be different, may be sufficient to disrupt the drift pattern so that a drift to the right may not be present. During violent gales, the ice may drift at the rate of 50 or more miles per day, especially in areas of strong currents, but drifts of a few miles per day are more common in the central Arctic Basin. The major outlfow from the Arctic Ocean is along the east coast of Greenland in the East Greenland Current where drifts of 50 miles a day or more are common.

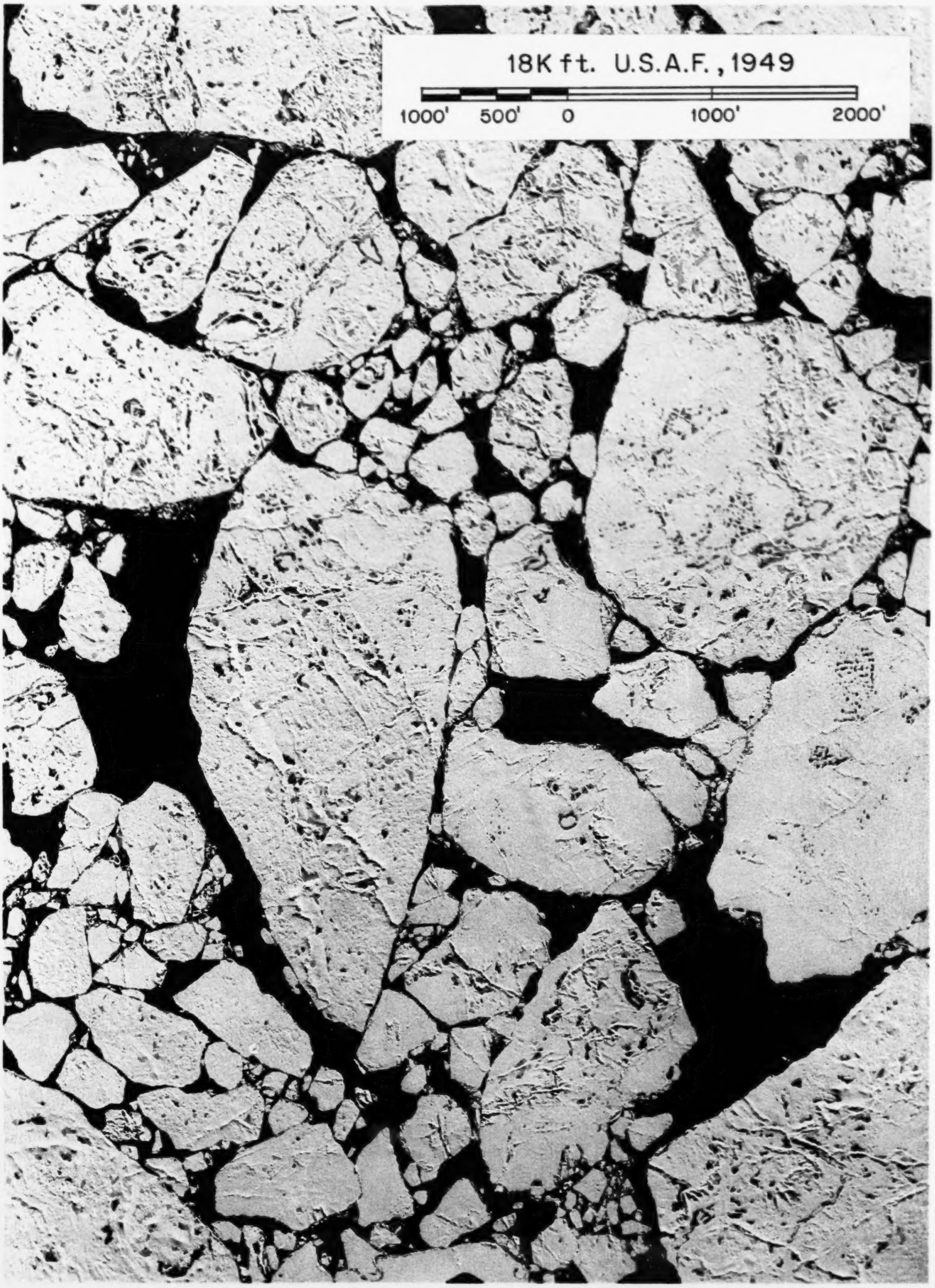
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Figure 1. Arctic Ocean in the summer from an altitude of 18,000 feet. The picture shows an area about 1 1/2 nautical miles long and a little over one nautical mile wide. U.S. Air Force photograph.

With the coming of warmer weather and higher angles of the sun, the ice begins to melt. This is a very slow process at first. Because of its color, ice relfects a high percentage of the sun's energy, thus keeping the melting at a low rate. Eventually, however, enough heat from the sun is absorbed so that pools of melt water begin to form on the surface of the pack. These pools act as "black bodies" - that is, they absorb a very high percentage of the sun's energy, so that once puddles begin to form on the surface, melting is greatly accelerated. Soon the pack is well spotted with puddles, and the deterioration of the ice proceeds rapidly..

Many of the Arctic islands are barren and, due to steepness, may have little snow cover in the winter. Dust from this land area often blows out onto the ice. Being dark in color, this dust absorbs large amounts of heat which speeds up the melting process. Attempts have been made with some limited success to take advantage of this in selected areas where dust, soot or coal dust, for example, is deliberately spread on the ice to speed up the melting process. Experiments in this field have been made to free harbors of ice to allow ships to enter sooner than would have been possible under normal conditions.

As the ice warms up, the concentrated brine pockets trapped within the ice begin to enlarge as they melt the ice surrounding them. Tiny channels are melted down through the ice which lets the brine escape. These channels at first tend to make the ice porous and soft and thus relatively weak. They also results in a "freshening" of the ice left behind. Furthermore, as alternate freezing and thawing takes place in the spring, these channels left by the escaping brine fill up with fresh melt water which in turn freezes when the temperature drops. Thus the ice in the late spring is likely to be nearly fresh and nearly as hard as natural fresh water ice. After the first year, ordinary sea ice is usually so fresh that melt water puddles on its surface can be used as fresh water reservoirs for ships. The whalers in the last century took advantage of this to keep themselves supplied with fresh water far from land.

As the thawing proceeds, the heat absorbed by the melt water pools causes these pools to work their way down through the entire thickness of the pack ice thus greatly weakening the floes which may then break up into small pieces. As soon as any great amount of open water forms, wave action developes which erodes and melts away the edges of the floes. Floes near the open edge of the pack are frequently carved and eroded into greatly contorted shapes with caves and valleys in them.

A relatively small part of the ice in the Arctic Basin is carried out by the currents. The East Greenland Current carries most of that, and the lesser currents flowing among the Canadian Arctic Islands carry smaller amounts. A minor amount passes irregularly out through Bering Strait between Alaska and Siberia. A larger amount of ice melts each year within the Arctic Ocean, but even so, the Arctic Ocean as a whole can be considered ice-covered throughout the summer. Only the fringes open up significantly. (See Figure 1.)

In the Antarctic, on the other hand, a major portion of the sea ice surrounding the Antarctic Continent either drifts off into warmer water or else melts in place each year. In the Weddell Sea south of the Atlantic Ocean, a large amount of ice is retained from year to year. In the Ross Sea, south of the Pacific Ocean, ice may remain throughout the summer of some years and not others.

The above discussion has been about sea ice - that is, ice formed from sea water. Not all of the ice in the sea is of this nature. Although much less in total volume than sea ice, icebergs, which are made up of fresh water ice, are of importance in any discussion of ice in the sea because of their gigantic size and resistance to melting and their potential hazard to ships operating far from the cold Arctic and Antarctic waters. In the north, snow falling on Greenland and a few of the other large Arctic islands accumulates in such thickness that it does not all melt off during the summer. As this accumulation goes on over the years, pressure caused by the depth of snow causes great compaction and eventually the conversion of the compact snow into solid ice. Under the pressure of hundreds of meters of ice, these massive formations, known as glaciers, behave as if they were a very viscous fluid. They gradually flow down valleys until they may reach the ocean where they break off in huge chunks to form icebergs. (See Figure 2.)

Because the density of ice is about 0.9 and that of water of approximately 1.0, roughly 9/10th of the iceberg is below the surface. It must be kept in mind that this is a mass ratio. That is, an iceberg 100 meters in height above the water does not necessarily extend 900 meters below the surface. Rather, for every kilogram of ice above the surface, there are 9 kilograms below the surface to provide flotation. This may take the form of a greatly expanded under-water body with vast shelves or ledges extending far out to the sides from the part of the berg showing above the water.

In the Antarctic, where the blocky straight-sided bergs are common, the 9:1 ratio of underwater to above water mass may result in a draft almost 9 times the height. It should be remembered, however, that the upper part of a blocky berg may be compacted snow and therefore appreciably lighter than the ice below it. But in the Arctic, most of the icebergs which appear in the shipping lanes are of an irregular shape; the underwater portion may be much wider than the part which shows, and therefore far less than 9 times as deep. (See Figure 3.)

It might be well to take a moment to describe the reason for the difference between the common Antarctic bergs and the common Arctic ones. As most students will know, the Antarctic is a huge, high continent surrounded by water. In contrast, the Arctic consists of a central Arctic Ocean almost surrounded by land masses. Because of the moderating effect of large volumes of water upon the climate, the central Arctic has a somewhat milder climate than does the Antarctic. The enormous bays and gulfs found along the margin of the Antarctic continent have formations known as ice shelves. These possibley originated in ages past as sea ice which survived the summer melting and built up to greater thickness each winter because of the accumulated snowfall. The weight of the compacted snow pushed the original ice down into the water, and in some areas the upper surface may be 30 meters or more above water, while the shelf may extend to a depth of 250 meters or more below the surface. Glaciers forming on the continent behind these shelves exert pressure against the inshore side of the shelves pushing them gradually out to sea. Periodically, massive pieces break off and drift out to sea as so-called "tabular bergs." These bergs are generally flat on top with straight sides, and bergs with dimensions of over 100 miles on a side have been reported.

In the Arctic, conditions are such that huge ice shelves are not formed. In limited areas on the northern Canadian islands, moderate ice shelves form, and the ice islands which have been used as scientific stations in the Arctic Ocean originated from these formations. However, most of the Arctic bergs are formed from glaciers - mostly Greenland glaciers - which descend steeply to the sea. The bergs which break off from these glaciers tend to be highly irregular in shape with many peaks and pinnacles. (See Figure 3.) They also contain a multitude of cracks and flaws which cause them to break up into smaller irregularly shaped pieces. Pebbles and rocks which are picked up by the glaciers as they scrape their way down the valleys are carried for vast distances to sea and deposited on the ocean floor when the ice melts.

When an iceberg breaks off from a glacier or an ice shelf, the process is known as "calving." Icebergs in turn calve smaller pieces. A fragment of an iceberg about the size of a house is known as a bergy bit. Smaller pieces the size of a grand piano are called growlers.

Because of their immense size and because long, jagged under-water projections are likely to be present, bergs are particularly dangerous to ships. The SS Titanic was merely the largest and most famous of hundreds of ships which have had holes torn in their hulls by projections from icebergs.

Bergs, because they ride so deeply in the water, tend to follow currents rather than winds. It is a common sight in the pack ice of Baffin Bay to see icebergs moving up-wind through pack ice, rafting the sea ice up ahead of themselves and leaving open wakes behind. Small vessels trapped in pack ice and threatened by pressure from the pack have frequently taken advantage of this feature. If they are able to make their way into the lee of an iceberg, they may find open water in which to ride safely.

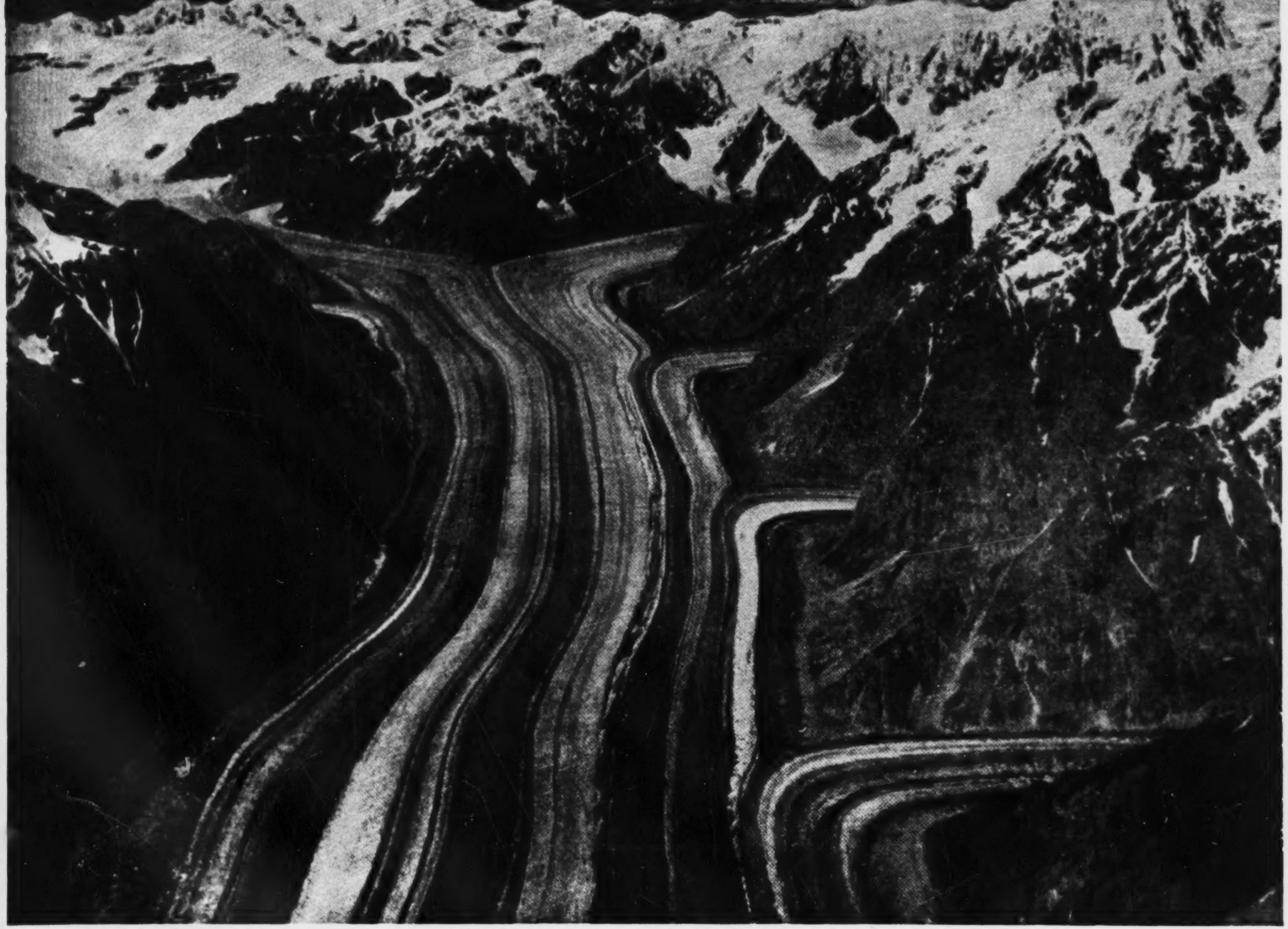


Figure 2. Barnard Glacier, Alaska. Numerous tributary glaciers from the sides of the main stream carry dark stripes of rocks and soil from the sides of their valleys. Photo by Bradford Washburn.

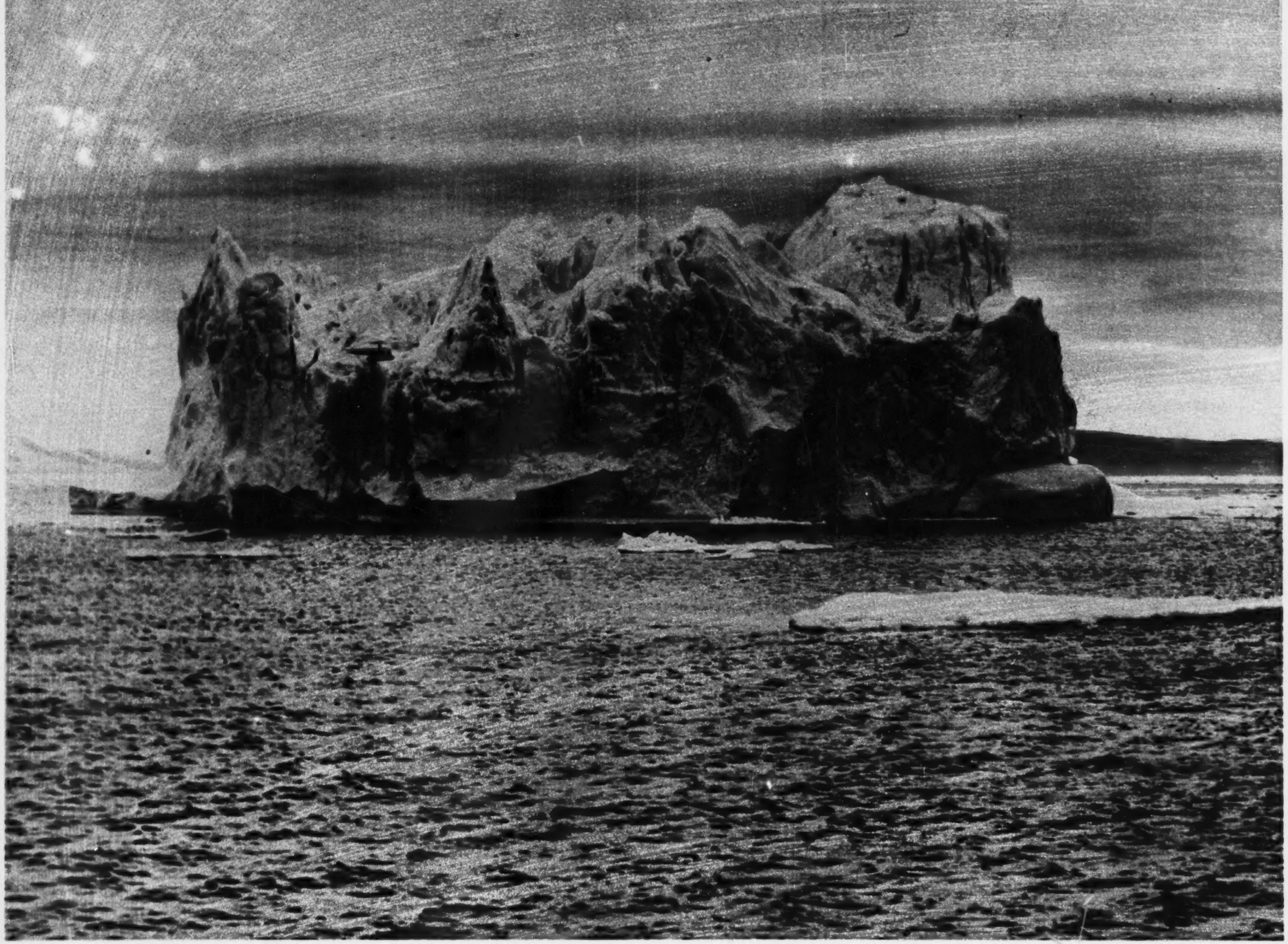


Figure 3. Large iceberg in Baffin Bay. Note the helicopter near the left side of the berg. U.S. Navy photograph.

Because of their great size, icebergs melt very slowly in the cold waters of the North Atlantic. Figure 4 illustrates the paths along which icebergs drift from their source into the North Atlantic. Occasionally an iceberg will get into the warm North Atlantic Drift where it wastes away more rapidly, but large remnants of bergs have been sighted near Bermuda and amongst the islands of the Azores. These are rare and isolated instances, however.

The International Ice Patrol, operated by the U. S. Coast Guard, spends several months each year surveying the iceberg situation in the North Atlantic and issuing warnings of the presence of icebergs and pack ice. In addition to surveys from airplanes and reports from ships which the Ice Patrol uses to draw up ice predictions, oceanographic surveys are also made. From samples of the water off the coast of Labrador, the Ice Patrol personnel compute the direction and speed of the currents and forecast ice movements accordingly. Experiments have been carried out marking bergs with bombs of colored dyes in order to enable the Patrol to track the bergs' movements.

Attempts to demolish bergs by gun fire, bombs, torpedoes and thermite charges have not produced notable success. It is impossible to bring enough heat to bear on the berg to melt any appreciable amount of the ice, and the bergs have been pretty much unaffected by this type of treatment.

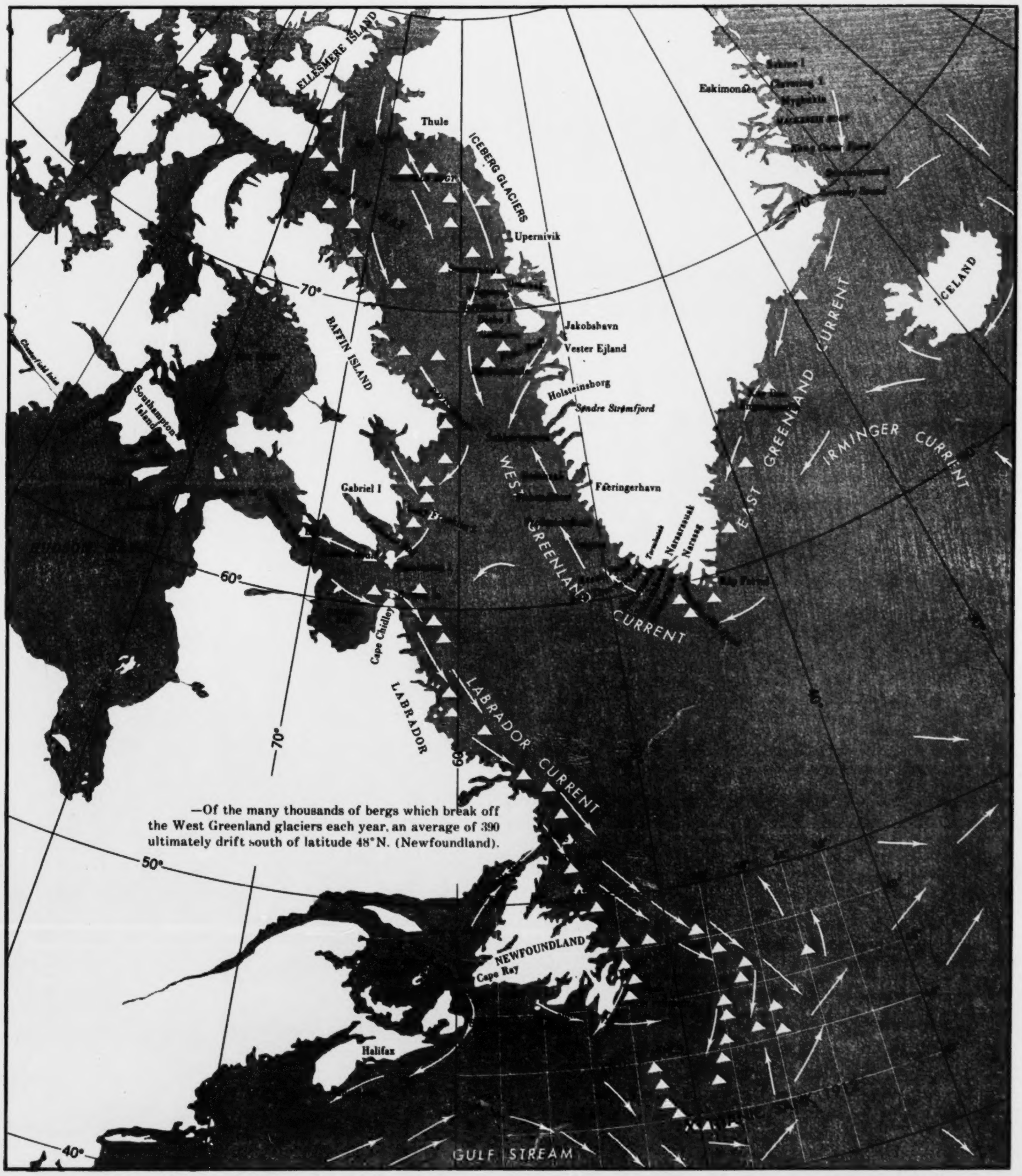
The U. S. Naval Oceanographic Office has been engaged for many years in making both long-range and short-range ice forecasts so that ships will be able carry supplies safely to the Arctic bases in Greenland and Canada during the summer months. A great many factors are considered in making the forecasts. For example, past weather records are examined in an attempt to estimate just how thick the ice might be in the first place. Then long range weather forecasts are studied to arrive at an estimate of how fast the ice can be expected to melt. Warm, sunny weather brings great amounts of heat to bear on the ice surface, but on the other hand, clear nights permit back reflection which may re-freeze much of the ice which was melted during the clear days. The direction and duration of the winds are important both as they affect the temperature of the air and as they move or prevent the movement of the ice out of the bays and inlets.

For shorter-range forecasts, on-the-site inspections, usually from aircraft, are carried out to determine the amount of ice present. Then from knowledge of local winds and currents plus short-range weather forecasts, the ice observers make estimates of when the ice in a given area might break up or move out, or estimates will be made of the best route to try to pass through or around an ice-infested area.

The activities of icebreakers in some local areas can be of importance. If an icebreaker can get into a frozen harbor and break up the cover, the fragmented ice may drift out with the wind and current a matter of weeks earlier than would have been the case under natural conditions.

The conventional icebreaker is designed with a "cutaway" bow. That is, the bow slopes back below the waterline to permit the ship to ride up onto the ice thus bringing its enormous weight to bear down directly on the ice. When it breaks through, it moves forward, rides up, and repeats the breaking process. Recently an ice plow has been developed which takes advantage of the fact that it is easier to break ice by lifting from below than by bearing down on it from above because water lends support to the ice in the latter case. The so-called "Alexbow" ice plow (named from its inventor, a Canadian named Alexander) has an additional advantage over conventional icebreakers. When the usual type of icebreaker makes its way through ice pack, it forces the ice down under the hull, and after the ship passes, the ice floats up and clogs the channel astern. A channel clogged with broken ice is almost as much of an obstacle to a cargo ship as an unbroken channel. In addition, the ice-filled channel quickly refreezes.

The ice plow, like a snow plow, throws the ice up and to the side. It comes to rest on the ice on either side of the plowed channel, and the following ships are not encumbered by it. Whether or not ice plows can be made stout enough and with enough flotation to handle really heavy Arctic pack remains to be seen, but in moderate ice such as is found in the Great Lakes, the St. Lawrence Seaway, and the fringes of the Arctic, the ice plow appears to be a success.


ELLESMERE ISLAND
Thule
ICEBERG GLACIERS
Upernivik
Eskimonaes
Sabine I
Mackenzie Bugt
70°
70
ICELAND
BAFFIN ISLAND
Jakobshavn
Vester Ejland
Holsteinsborg
Søndre Strømfjord
Southampton Island
EAST GREENLAND CURRENT
IRMINGER CURRENT
WEST GREENLAND CURRENT
Gabriel I
Faeringerhavn
Narsarsuak
Narssaq
60°
Cape Chidley
LABRADOR
LABRADOR CURRENT
70°
60
50°
NEWFOUNDLAND
Cape Ray
Halifax
40°
GULF STREAM

—Of the many thousands of bergs which break off the West Greenland glaciers each year, an average of 390 ultimately drift south of latitude 48°N. (Newfoundland).

Figure 4. Drift of icebergs from their source into the North Atlantic. U.S. Navy Hydrographic Office.

Because of the slowness with which the ice melts after the temperature gets above the melting point, the navigation season in the polar regions is off-set from the warmest part of the summer. That is, melting may commence in June and July, but the melting is slow until the puddles are well formed on the surface of the pack, and it is well into August and September before the best ship navigation season is at hand. By this time, the weather has already begun to cool off, but re-freezing does not become seriously effective until well into October. However, there are additional considerations. In June and July there is daylight throughout the 24 hourse in the Arctic. By September and October, the darkness is becoming prolonged, and this makes operating in ice additionally hazardous. Furthermore, the weather in October is likely to be much stormier than it is earlier in the season, and this must also be taken into consideration. Within the pack ice, strong winds are able to build up heavy pressure, and outside the pack the seas get very rough.

At the other end of the season, there is a similar lag. Although the weather is coldest in January and February, because of the slowness of the freezing, the ice thickness and coverage do not reach their maximum until March and April. Thus although the coldest weather is in midwinter, and warmest is in mid-summer, the greatest amount of ice is present in the spring, and the least is present in the fall. These factors must all be considered when planning polar operations.

Very little has been said about the Antarctic. Actually, the situation is roughly comparable, with the seasons reversed in the southern hemisphere. In addition, the climate is somewhat more rigorous in the Antarctic than in the Arctic because of the greater land mass in the former. A major factor to be considered also is that the Antarctic Continent is surrounded by the stormiest seas in the world. This makes the Antarctic a very difficult place to approach in any but the largest ships, and large ships are not usually the most efficient ships for operating inside pack ice. However, because of the greatly increased scientific interest and activity in the Antarctic in recent years, more and more shipping is involved in Antarctic operations each year.

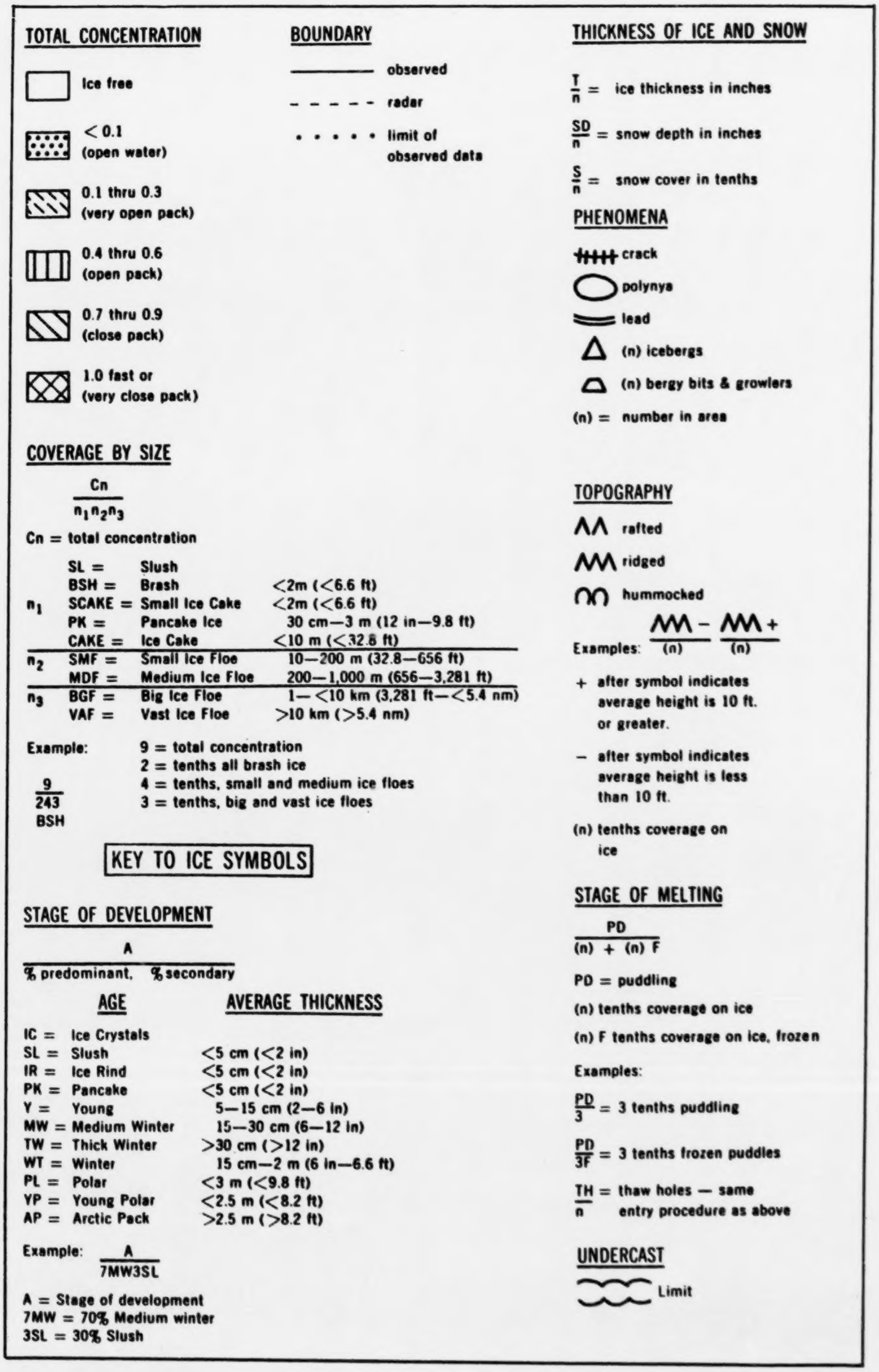
As was mentioned above, the Oceanographic Office is the government agency responsible for providing ice information. Some of their forecasting methods have already been touched on. "Ice Atlases" are issued which show average ice conditions, by month, throughout the year with additional information regarding maximum and minimum amounts which have been found in the past.

Months in advance of the ice navigation season, airplanes carry ice observers on regular reconnaissance flights over the Arctic. Using various simple codes, the observers relay ice information to the Oceanographic Office by radio, and ice charts are drawn up. Examples of these charts and the codes are shown in the accompanying illustrations. (See Figures 5-7.)

Before shipping enters the ice area, additional plane flights are made, and icebreakers may enter the pack to scout the situation. For close range ice observations, the icebreakers carry helicopters which fly out ahead of the ship to scout the best route through the ice. The general rule of thumb is that the shortest distance between two points in the Arctic is around rather than through the ice. However, in high latitude work it is frequently necessary that the ships work their way directly through the ice by any means possible to reach their destination.

Thin-skinned or even reinforced ships of conventional design are very vulnerable to ice damage. Even when specially strengthened for ice work, the usual hull form of a cargo ship is not ideal for working in ice. Moreover, damage to the propeller and rudder is always a major threat.

In moderately heavy or consolidated pack ice, the icebreakers may find it necessary to take cargo ships in tow. This is a cumbersome and inefficient method of traversing pack ice, but there may be no feasible alternative. When distant or local storms produce pressure in the pack, the icebreaker may be forced to attempt to prevent dangerous build-up of pressure around the hulls of the cargo ships to prevent ice from being pushed right through the metal plates. Polar pack under pressure has been the undoing of hundreds of ships in the past, and even today when the ships are better equipped to operate in ice pack than ever before, there are frequent tense situations. However, as ice observing, ice forecasting, and icebreaking techniques continue to improve, more and more shipping moves through the polar seas than ever before.



KEY TO ICE SYMBOLS

TOTAL CONCENTRATION

☐ Ice free

▒ < 0.1 (open water)

▨ 0.1 thru 0.3 (very open pack)

▥ 0.4 thru 0.6 (open pack)

▧ 0.7 thru 0.9 (close pack)

▩ 1.0 fast or (very close pack)

COVERAGE BY SIZE

$$\frac{Cn}{n_1 n_2 n_3}$$

Cn = total concentration

n_1	SL =	Slush	
	BSH =	Brash	<2m (<6.6 ft)
	SCAKE =	Small Ice Cake	<2m (<6.6 ft)
	PK =	Pancake Ice	30 cm—3 m (12 in—9.8 ft)
	CAKE =	Ice Cake	<10 m (<32.8 ft)
n_2	SMF =	Small Ice Floe	10—200 m (32.8—656 ft)
	MDF =	Medium Ice Floe	200—1,000 m (656—3,281 ft)
n_3	BGF =	Big Ice Floe	1—<10 km (3,281 ft—<5.4 nm)
	VAF =	Vast Ice Floe	>10 km (>5.4 nm)

Example:

$$\frac{9}{243}$$
BSH

9 = total concentration
2 = tenths all brash ice
4 = tenths, small and medium ice floes
3 = tenths, big and vast ice floes

STAGE OF DEVELOPMENT

$$\frac{A}{\%\ \text{predominant},\ \ \%\ \text{secondary}}$$

AGE		AVERAGE THICKNESS
IC =	Ice Crystals	
SL =	Slush	<5 cm (<2 in)
IR =	Ice Rind	<5 cm (<2 in)
PK =	Pancake	<5 cm (<2 in)
Y =	Young	5—15 cm (2—6 in)
MW =	Medium Winter	15—30 cm (6—12 in)
TW =	Thick Winter	>30 cm (>12 in)
WT =	Winter	15 cm—2 m (6 in—6.6 ft)
PL =	Polar	<3 m (<9.8 ft)
YP =	Young Polar	<2.5 m (<8.2 ft)
AP =	Arctic Pack	>2.5 m (>8.2 ft)

Example: $\frac{A}{7MW3SL}$

A = Stage of development
7MW = 70% Medium winter
3SL = 30% Slush

BOUNDARY

observed
radar
limit of observed data

THICKNESS OF ICE AND SNOW

$\frac{T}{n}$ = ice thickness in inches

$\frac{SD}{n}$ = snow depth in inches

$\frac{S}{n}$ = snow cover in tenths

PHENOMENA

crack
polynya
lead
Δ (n) icebergs
(n) bergy bits & growlers
(n) = number in area

TOPOGRAPHY

rafted
ridged
hummocked

Examples: $\frac{\text{ʌʌʌ} -}{(n)}$ $\frac{\text{ʌʌʌ} +}{(n)}$

+ after symbol indicates average height is 10 ft. or greater.

− after symbol indicates average height is less than 10 ft.

(n) tenths coverage on ice

STAGE OF MELTING

$$\frac{PD}{(n) + (n)\ F}$$

PD = puddling

(n) tenths coverage on ice

(n) F tenths coverage on ice, frozen

Examples:

$\frac{PD}{3}$ = 3 tenths puddling

$\frac{PD}{3F}$ = 3 tenths frozen puddles

$\frac{TH}{n}$ = thaw holes — same entry procedure as above

UNDERCAST

Limit

Figure 5. Symbols used on ice observations charts to indicate amount and types of ice present. U. S. Naval Oceanographic Office.

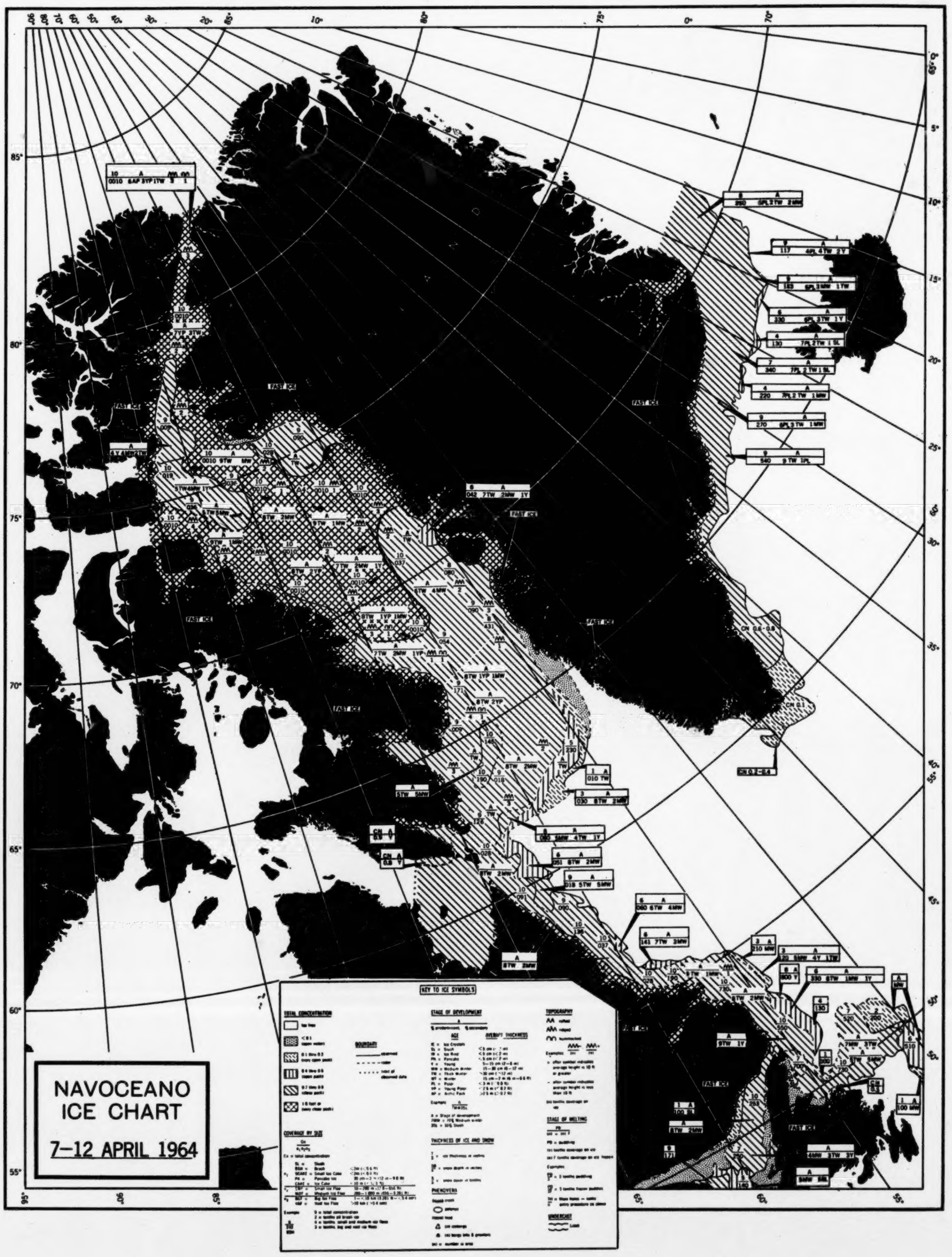

NAVOCEANO
ICE CHART
7–12 APRIL 1964
KEY TO ICE SYMBOLS
FAST ICE

Figure 6. Ice situation in April 1964 at the height of the ice season. U.S. Naval Oceanographic Office.

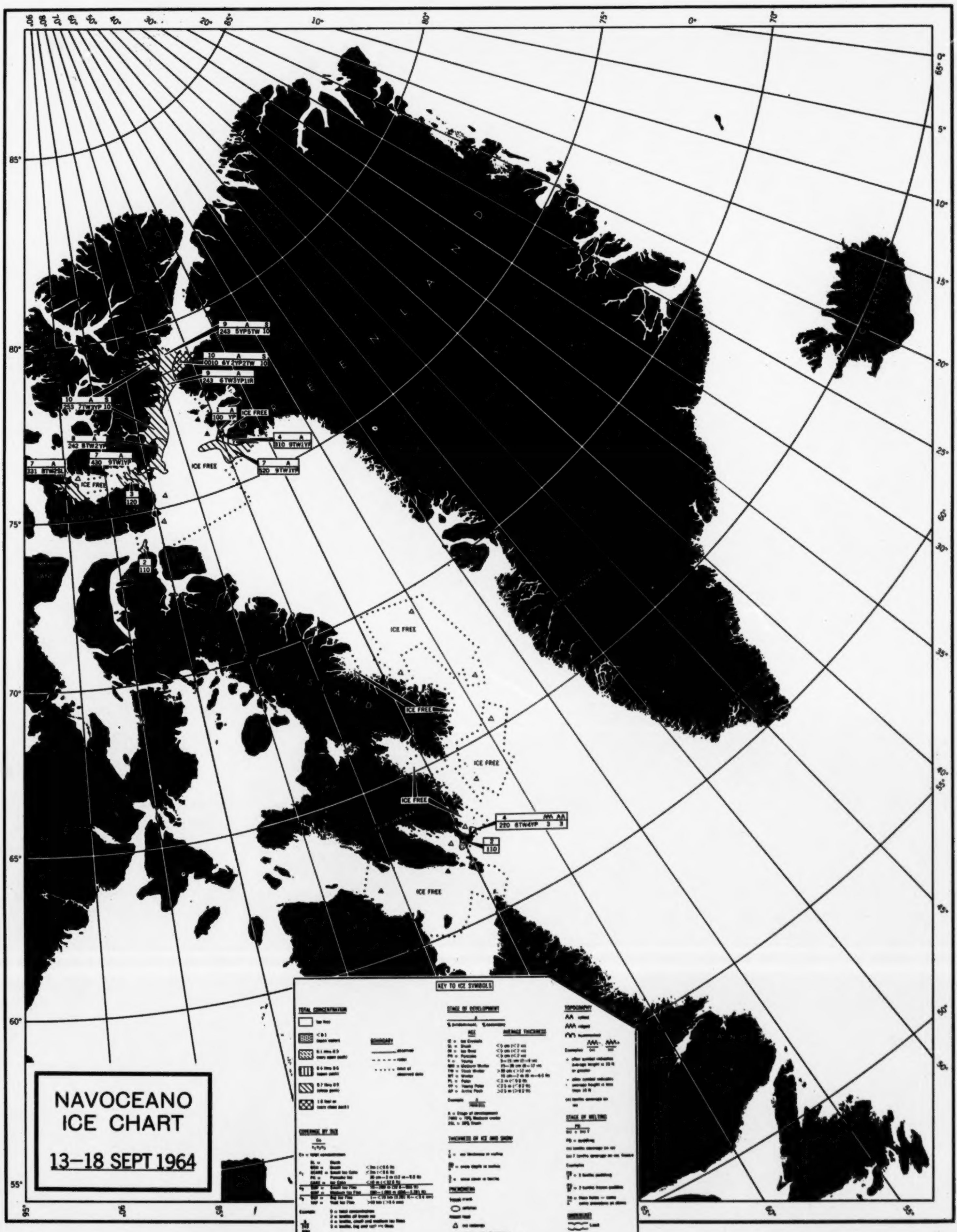

NAVOCEANO
ICE CHART
13–18 SEPT 1964
KEY TO ICE SYMBOLS
ICE FREE
GREENLAND

Figure 7. Ice situation in September 1964 at the height of the navigation season. U.S. Naval Oceanographic Office.

The Russians are especially advanced in ice operations. Having an Arctic shore thousands of miles long, they have developed icebreakers and ice navigation techniques far in advance of those of most other countries. Scandanavian countries have also been active in this field in the north, and Argentina and Chile have icebreaking fleets for Antarctic operations. The United States and Canada have joint interests in the areas north of our two countries, and cooperative ventures have been frequent and will undoubtedly continue.

Atomic power would seem to hold a number of advantages for icebreakers - enormous power plus practically unlimited range. So far, only the Soviet Union has built an atomic powered icebreaker, the Lenin, but other countries may follow. Canada is presently engaged in developing the vast resources of her far northern areas, and increased interest and activity in the Arctic is bound to increase the study of sea ice.

Early interest in the Arctic came about with attempts to discover a feasible northwest passage to the Orient. The first Arctic explorers endured incredible hardships to explore vast territories by the inefficient means of sailing ship and sledge. By the mid-1800's, most of the major Arctic islands and shores both in America and Eurasia had been charted at least roughly.

In the very late 1800's, the Norwegian scientist Nansen had a ship designed and built to operate in the polar pack. The Fram was a small wooden vessel of immense strength which was designed with a rounded hull which, it was hoped, would react to lateral pressure from the ice by being pushed up onto the surface of the ice without harm. The idea worked, and in three years Nansen and his party drifted across the Polar Basin from Siberia to East Greenland. A great deal of scientific information about the far north was discovered on this voyage. Nevertheless, except for individual exploits such as that and Peary's trip across the ice to the Pole in the early part of this century, travel in the high Arctic never reached the point where it was much more than an adventure until airplanes and submarines entered the field. Now it is readily feasible to transport scientists to almost any part of the Arctic or Antarctic in relative safety and comfort to carry out all sorts of research work.

Nuclear submarines have traversed the polar sea at all seasons of the year and have surfaced almost at will in any part of the pack ice. Equipped with upward-looking fathometers, they are able to scan the ice cover above them and pick open leads or at least relatively thin places to rise above the surface.

Airplanes equipped with winches and scientific instruments have made landings on re-frozen leads all over the Arctic Basin. The Russians undoubtedly lead in this field of scientific investigation, but the United States and Canada are both active, with scientific stations within the polar back.

References

The following are two excellent books on the Arctic which may interest students.

Ellsberg, Commander Edward, 1938. *Hell on Ice, The Saga of the "Jeannette."* Dodd, Mead and Co., New York.

This is an historically accurate, fictionalized account of an early U. S. expedition to the Arctic which came to grief north of Siberia in the 1880's.

Mirsky, Jeannette, 1948. *To the Arctic! The Story of Northern Exploration from Earliest Times to the Present.* Alfred A. Knopf, New York.

This is an historical review of Arctic exploration with an introduction by Wilhajalmur Stefansson.

Maps and charts:

U. S. Naval Oceanographic Office, 1946. *Ice Atlas of the Northern Hemisphere.* 106 pp.

The Navoceano Ice Charts are also published by the U. S. Naval Oceanographic Office, Department of the Navy, Washington, D. C. 20390.

9. CHEMICAL OCEANOGRAPHY:

Its Substance, Aims, and Implications

by Ralph F. Vaccaro
Woods Hole Oceanographic Institution

Introduction

Chemical oceanographers study the oceans in terms of natural laws which relate to the composition and transformation of matter. They concentrate on the unique properties of water and seawater and seek a better understanding of the various hydrochemical and biochemical cycles which characterize the oceans.

The overall objective of the chemical oceanographer is to assign rates, routes, reservoirs, and residence times for the variety of chemical entities which enter the oceans from land or the atmosphere and which are finally deposited in marine sediments. Progress in all phases of marine science in some way depends upon a coordinated approach to the oceans via both established and new chemical concepts. For example, the physical oceanographer relies on chemistry to help describe water masses and their role in the transport of heat and salt. The marine biologist requires chemistry to advance his understanding of oceanic life processes such as photosynthesis and respiration. A major objective of the marine geologist is to describe the sequence of events which accounts for the presence or absence of specific chemical entities in the sea. Finally, the natural occurrence of water as ice, liquid, and vapor is of paramount interest to the meteorologist who is concerned with the energy exchanges which accompany freezing, melting, and evaporation and which generate our weather systems.

The General Importance of Water

The physical and chemical characteristics of water per se as well as its great abundance have played a fundamental role in the earth's development. Because of its extreme mobility and its effectiveness as a solvent, water is unexcelled on our planet as an agent of erosion, and its potential in this respect is strikingly demonstrated by the vastness of the Grand Canyon of the Colorado River. Water more than any other substance is considered responsible for the origin and persistence of life on earth. It is essential in plant and animal nutrition and is a component of the cells of all living tissues.

The early Greeks believed that matter consisted of four "elements" - earth, water, air, and fire. Of these only water, which represents a bonding of two hydrogen atoms with one oxygen atom, is still considered a valid chemical entity. The Romans also understood the significance of water as a mainstay of life, and their ability to construct a great system of aqueducts was an important reason for the success of their civilization. At the same time, history records that many promising civilizations withered and disappeared prematurely because of insufficient or unsuitable water resources. Fortunately, the water reserves of our own country are still abundant and, if properly managed, almost unlimited. However, great vigilance will be necessary to protect this vital natural resource from the disruptive influences of man and his propensity to regard the waterways as a convenient means of washing away his domestic and industrial wastes.

Certain properties of water are particularly well established, and water has always provided a convenient object of reference with which to compare the behavior of other chemical entities. For example, measurements of specific gravity, hear capacity, and thermometry are all scaled in terms of pure water. Likewise, known chemical and biochemical reactions are almost exclusively defined for aqueous solutions of interacting substances.

Most chemical reactions involving water proceed slowly and nonviolently because the chemical bonds between hydrogen and oxygen are strong and not readily broken. Water is also the most effective solvent known, yet water soluble materials typically undergo a minimum amount of chemical change and are usually recoverable in their original state. Finally, the fact that water constitutes 75 to 90 percent of all living plants and animals is a fitting tribute to its incomparable role on our earth.

Geochemical Origins of Seawater

The vast accumulation of water and salt which occupies the ocean basins probably originated from long-term rather than short-term geological processes. Apparently the earth's primordial atmosphere contained insufficient water to account for the volume of the modern oceans. Hence it is unlikely that water which condensed during atmospheric cooling provided the major source of ocean water; More likely, the oceans' basins were gradually filled, as the continents were being built-up, by water, in various forms or combinations, emerging from the interior of the earth via hot springs and volcanoes. The relatively short-term changes in sea level caused by the various ice ages do not alter this picture appreciably since the fractional amounts of seawater converted to ice were relatively small in terms of the size of the oceans.

In tracing the origin of salt in the oceans more than one geological process must be considered. The presence of cations such as potassium, sodium, calcium, and magnesium can be reasonably well accounted for on the basis of rock weathering and subsequent transport by wind and water. On the other hand, anions such as chloride, bromide, and bicarbonate cannot be accounted for by weathering and probably originated as gases from fumaroles and volcanoes which passed through the atmosphere and became chemically bound in seawater.

Atmospheric gases can penetrate and be exchanged across the sea surface relatively fast, hence a marked similarity between the gaseous contents of the ocean and the atmosphere is to be expected. Within the oceans, the fate of dissolved gases depends upon their dispersal by water movements and mixing as well as their ultimate participation in chemical and biochemical reactions. Until the advent of plant photosynthesis, some three billion years ago, neither the ocean nor the atmosphere contained an excess of free oxygen. The subsequent invasion of oxygen into the sea led to the oxidation of reduced seawater constituents and to the gradual development of the free oxygen levels which prevail today.

Thermal Properties of Water and Seawater

The temperature at which seawater freezes varies inversely with its salt content. Distilled water (saltless) freezes at 32°F [0°C] while seawater at the average salinity of the oceans (3.47 per cent salt) freezes at about 29°F [about -2°C]. The surface temperatures in the ocean range from 28.7°F [-1.8°C] in polar areas to 90°F [32°C] in the Persian Gulf, and increase to 150°F [65°C] in the bottom water of the Red Sea. Table I shows the relative size of the sea surface areas which correspond to a variety of temperature ranges. The fact that about half the surface area of the oceans is restricted to a mild and comfortable temperature range of 70 and 85°F [21 and 29°C] is noteworthy and descriptive of how the oceans tend to minimize extreme winter and summer changes in temperature. The oceans function as the world's greatest heat trap because of the penetration and conversion of solar radiation to heat near the sea surface within tropical and semi-tropical latitudes.

The pronounced tendendy for water to resist temperature changes and behave as an environmental thermostat is largely but not entirely due to its high specific heat requirement. Other water properties which enhance this tendency include effects from evaporational cooling, heat loss during freezing, and an ability to mix rapidly. The heat regulation provided by water is also important in minimizing excessive heat gain or loss through the metabolic processes of warm blooded animals. For instance, a man weighing 165 lbs. must ingest about 2,400 large calories per day and must dissipate a heat equivalent of 32°F [0°C] to maintain a constant body temperature. A similar estimate for 165 lbs. of quartz would necessitate a comparable heat loss equivalent to 150°F [65°C].

Table I

Approximate distribution of oceanic surface temperature

Annual range of surface temperature °F	Percent area of oceans	
35 or below	12.5	
35 - 40	4.9	
40 - 45	3.6	
45 - 50	4.8	
50 - 55	5.2	
55 - 60	5.5	
60 - 65	5.9	
65 - 70	7.5	
70 - 75	10.2	Fraction of Total = 50%
75 - 80	17.0	
80 - 85	22.8	
85 - 90	0.1	

The major source of heat with respect to the oceans is solar radiation, although some additional heat is provided by heat flow through the bottom. Most of the energy arriving at the surface is used to evaporate water while a lesser fraction is lost via back radiation to the atmosphere. These limitations plus the high specific heat of water itself insure that less than half of the sun's radiant energy supply at the ocean's surface is transferred as heat down through the water column. Below the surface the ocean almost invariably shows a decrease in temperature with depth because colder water is usually heavier and sinks below warmer water.

When salt free water is cooled it attains maximum density at 39°F [4°C]. Thus winter cooling of freshwater ponds and lakes within temperate latitudes causes an annual fall turn-over whereby dense surface water sinks and is displaced by lighter deep water. Both the replenishment of plant nutrients at the surface and a delay in the onset of icing conditions are important consequences of this behavior.

Unlike fresh water, the greatest density of seawater does not occur at 30°F [4°C] since the salt content is usually high enough to lower the maximum density below the freezing point. However, since salt is excluded when seawater freezes, the surrounding seawater undergoes an increasedin density due to an increases salt content. Ultimately, a sufficiently high density may be attained so that sinking of water from the surface commences. The occurrence of cold, dense bottom water throughout the deepest areas of the oceans, regardless of latitude, is accounted for in this manner.

The Major Constituents of Seawater

The major constituents of seawater represent some eleven ionic species which comprise about 99 per cent of the total load of dissolved material. Because the distribution of these elements depends upon physical processes such as wind- and density-induced water movements which control mixing, they are sometimes called the conservative elements of the sea. The relative abundance, by weight, of these constituents after the concentration of fluoride is set at unity appears in Table II.

Besides being an excellent solvent, water has a marked tendency to convert dissolved solids into ionized particles. This is due to the dielectric capability of water which is one of the highest known. When common salt (NaCl) dissolves in water, a combination of positively charged sodium ions and negatively charged chloride ions are released and only a relatively small amount of undissociated sodium chloride remains. The quantities involved are described by the following equation and comparable relations could be shown for many other dissolved salts.

$$\overset{100\%}{\mathrm{NaCl}} \xrightarrow{H_2O} \overset{90\%}{\mathrm{Na^+ + Cl^-}} + \overset{10\%}{\mathrm{NaCl}}$$

Table II

Major Constituent	Relative Abundance mass per unit volume
Chloride	20,000
Sodium	11,000
Sulfate	3,000
Magnesium	1,300
Calcium	400
Potassium	400
Bicarbonate	150
Bromide	67
Strontium	8
Boron	4
Fluoride	1

Undoubtedly the earliest chemical observation conducted on seawater was the recognition of its salty taste. Modern oceanographers use the term salinity to describe the total amount of dissolved solids present in seawater. Studies on the fractional representation of the major seawater constituents have shown that all of the principal salts occur everywhere in about the same proportion. In effect, this observation suggests that salt representation stays essentially the same, but variability in the ratio, total salt:water, accounts for the observed salinity changes. Actually the salinity of seawater varies from 3.0% to about 3.6%, which in the more conventional salinity units of parts per thousand ($^{o}/oo$) would appear as 30 - 36$^{o}/oo$.

Low salinity seawaters contain a relatively large fraction of river water or ice melt, while high salinities can be caused by the partition of salt during freezing or by an excess of evaporation over the combined amount of rainfall plus river drainage.

To estimate salinity concentration by summing each of the major constituents independently would be tedious and impractical. Instead chemists take advantage of the constant ratio of salts in seawater by first establishing a chlorinity value which can be directly converted to salinity. Chlorinity measurements are usually obtained from a direct titration of the total halides with a standard solution of silver nitrate. Other analytical techniques such as measurements of electrical conductivity, specific gravity, and index of refraction can also be used to measure salinity. Once the chlorinity of a seawater sample is established, the salinity can be calculated according to the following expression:

$$\text{Salinity, } {}^{0}/oo = .03 + 1.805 \ (\text{Chlorinity, } {}^{0}/oo)$$

The density of seawater, or its mass per unit volume, depends upon three variables, temperature, pressure, and salinity. The average sample of seawater weighs 63.5 lbs. per cubic foot while distilled water weighs but 62.0 lbs. per cubic foot. Therefore, the average density (specify gravity) of seawater is about 1.025 which expressed in terms of σ_t (grams per liter in excess of 1 kilogram) would be 25.0. Besides increasing with cooling and salinity, density also increases with pressure due to the slight compressibility of seawater.

Colligative Properties of Seawater

The colligative properties of solutions are those which depend upon the presence of ions in solution. Increasing the ionic concentration of seawater depresses the vapor pressure and freezing point, but elevates the boiling point, osmotic pressure, and electrical conductivity. Since all of these changes are caused by ionic behavior, if any one of them is measured, the others can be computed.

Vapor pressure is that pressure exerted by a gas or vapor when a state of equilibrium is reached between a solution and its atmosphere. If the vapor pressure of a liquid exceeds that of its atmosphere, boiling results.

Osmotic pressure is the force exerted by a substance in solution which seeks to distribute itself uniformly throughout the entire volume of a solvent. It is measured indirectly as the force required to prevent the migration of solvent through a semi-permeable membrane which separates two different ionic concentrations.

The presence of ions in solution lowers the freezing point by an amount which is proportional to the ionic concentration. For example, the freezing point of a two percent solution of common salt is lowered twice as much below 32°F [0°C] as that of a one percent solution and two thirds that of a three percent solution.

An elevation of the boiling point also accompanies an increase in ionic concentration. As previously stated the boiling point of a liquid is the temperature at which its vapor pressure just exceeds the vapor pressure of its atmosphere. Thus lowering of the vapor pressure will raise the boiling temperature since the liquid must be heated to a higher temperature to regain its original vapor pressure.

Electrical conductivity is expressed as the reciprocal of the rate at which electrical energy is converted into heat when a standard potential is applied between two terminal electrodes. Besides increasing with salinity, it also increases with temperature.

The Latent Heats of Melting and Evaporation

We think of water as occurring in three principal states or phases; solid water (ice), liquid water, and gaseous water (water vapor). To initiate phase changes in the above direction, a definite amount of heat is required to convert each gram of ice to a gram of liquid water without changing the temperature. Comparable but much higher heat requirements are also necessary to convert liquid water into water vapor (evaporation). The heat exchanges associated with phase changes in the opposite direction, i.e., condensation and ice formation, are equal in magnitude but result in a gain rather than a loss of heat to the surrounding environment.

The latent heat of melting which refers to the number of calories required to convert one gram of ice at the freezing point to one gram of liquid at the same temperature is 80 calories or enough to raise the temperature of one gram of water from 32°F to 160°F.

The latent heat of evaporation refers to the number of calories required to convert one gram of liquid into vapor at the same temperature. The magnitude of this heat requirement depends upon water temperature but approximates 536 calories or enough heat to raise the temperature of a half pint of water by about 2°F.

Latent heat exchanges in nature tend to equalize and moderate temperature relations between the atmosphere and the oceans. Once seawater is cooled to the freezing point, its temperature does not change with additional cooling, which only increases the amount of ice present. Likewise, cooling of a humid atmosphere ultimately causes water condensation which in turn releases heat which exerts a moderating influence on the temperature of the atmosphere. It is also worth repeating that evaporation of water from the skin of warm blooded animals is an important means of regulating against high fluctuations in body temperature.

Pressure in the Sea

Every 33 feet or 10 meters of depth in the ocean increases the pressure by one atmosphere or 15 lbs. per square inch. Thus at a depth of 5,000 meters, which approximates the average depth of the oceans, the hydrostatic pressure amounts to about 7,500 lbs. per square inch. At the greatest known depth in the oceans, about 10,000 meters, the weight of the overlying water column amounts to 15,000 lbs. or 7.5 tons per square inch.

Color, Transparency, and Light Penetration

As on land, the sun provides the basic source of all energy in the ocean, and the heating of seawater via solar radiation has been shown to have a profound effect on the climate of our earth. Sunlight is also the driving force behind photosynthesis and growth by plants, and togehter these two processes provide the principal food source for all marine animals. In turn, a significant fraction of the world's population, especially in East Asia, depends on fish products to maintain a nutritionally satisfactory diet. Sunlight is also necessary for the vision of marine fishes and controls both the migrations and breeding of many marine species.

The blue color of seawater like the blue color of the sky is due to the molecular scattering of light. Coastal waters appear greenish-blue due to the influence of the yellow plant pigment, carotene. Frequently, the waters of estuaries and embayments are brown due to the amount and types of microorganisms and detritus in suspension. Plants and animals which live very near the surface are subjected to a mixture of light which extends from the near ultra-violet to the infra-red regions of the spectrum. However, much of the incident energy, especially the ultra-violet and the infra-red portion, is absorbed completely within 10 feet [3 meters] of the surface while the remaining portions of the spectrum are scattered downward to a degree that varies according to the clarity of the water. In the clearest seawater, blue light at a wavelength of about 460 millimicrons is most penetrating and is the color most prominently back-scattered. Under ideal conditions, a zenith sun over the open ocean is capable of blue light penetration, which would be visible to the human eye, at least to a depth of 2,600 feet [800 meters].

The Minor Constituents of Seawater

Besides the major constituents, seawater also contains an additional group of elements called the minor constituents, which total less than 0.3 per cent of total amount of dissolved solids. Despite their relative scarcity, the biochemical and geochemical importance of this group should not be underestimated. Usually, the minor constituents are divided into three different categories: (1) the principal nutrient elements, (2) the micronutrients, and (3) trace elements. New information on the nutritional requirements of marine organisms can be expected to alter the representation of elements within each of these categories.

In agriculture, the principal nutrient elements are nitrogen, phosphorus, and silicon as well as potassium, calcium, and magnesium. The latter three elements are classed as major constituents of seawater because the oceans contain them in amounts which exceed the nutritional requirements of marine plants. On the other hand, available nitrogen, phosphorus, and silicon are considered minor constituents of seawater since they are not always present in overabundance. Prolonged plant growth at or near the surface where light is suitable for photosynthesis often causes a depletion of these elements due to their biochemical conversion into living cell substance.

Together, photosynthesis and plant growth constitue the essential first steps in establishing the food chain of the sea. To sustain marine life, nutrient elements removed during plant growth must ultimately be returned in an available form to the photosynthetic zone. At each of the various trophic levels of the food chain, organic excretions and inert cellular remains are broken down by the activities of bacteria and animals so that ultimately the original ionic forms of the principal nutrient elements are regenerated and returned to solution.

When the regeneration of plant nutrients proceeds outside the zone of active plant growth, various mixing processes are responsible for their return to the surface. Sometimes in coastal areas this is accomplished by upwelling when nutrient-rich deep water replaces impoverished surface water as the latter is pushed seaward by prevailing winds. At other locations surface waters are enriched by the turbulence caused by currents passing over an uneven bottom or through narrow straits. In temperate zones where there is a marked seasonal variation in temperature, vertical convection helps maintain the annual supply of plant nutrients in the upper layer. Convection commences during winter cooling when the density of surface seawater increases sufficiently to initiate a sinking which in turn causes a compensatory upward movement of lighter, nutrient rich water from below.

The distribution of the micronutrient elements in the sea remains to be fully documented since procedural difficulties introduced by their extremely dilute concentrations often preclude reliable analytical estimates. However, many marine plants and animals are able to concentrate micronutrients up to 10,000 fold above that of the surrounding seawater. Many marine biolgoists believe that low concentrations of iron and magnesium in certain surface waters can limit the growth rates of plant populations. In addition, certain other trace elements including copper, zinc, molybdenum, and cobalt are also known to be essential for the growth of plants. Copper is concentrated in the soft tissues of many marine organisms such as oysters and also in hemocyanin, the respiratory pigment of crustaceans. Cobalt is an essential part of the vitamin B_{12} molecule and many marine organisms show enrichment tendencies which favor an accumulation of this element. Both iodine and bromine are highly concentrated in the brown seaweeds and iodine is extracted in commercial quantities from kelp in Japan. The body fluids of tunicates are notably rich in vanadium although the processes leading to its accumulation remain obscure.

Geochemically, the distribution of the minor elements is also of considerable interest, and it is to geochemists that we owe most of the available information on this subject. The dating of marine sediments by the detection of radioactive elements and their decay products has proven extremely rewarding and has accounted for much of the recent progress in this area. Finally, the increased use of nuclear fission during the past few decades has already led to the accumulation of measurable quantities of radioactive isotopes in marine organisms and sediments and re-emphasizes the continuing need for more definitive information on the distribution and role of minor elements in the sea.

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10. MARINE BIOLOGY

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Food Chain or Energy Dynamics of the Sea

One of the central ideas in all biology is that living things always exist as part of a functioning system. The system includes other living things and the nonliving physical and chemical environment. Marine biology is the study of the living system of the sea. All living organisms from bacteria to whales affect each other, they affect the physical and chemical environment. Marine biology's ultimate objective is to understand the nature of the living system of the sea, that is, what kinds of plants and animals are present in the sea, how they carry out their life processes, and how their lives interrelate. This is an ambitious goal and one that will require a great deal of effort in the future; but it is also an essential goal, one which we must work towards.

Marine biology's increasing knowledge of the sea is of primary imporance not as a means of supplying more food from the sea, although that is a minor benefit which will accrue. The real need for understanding the living system of the sea is that man and his civilization are part of that system and if the system is destroyed or damaged, man's existence is threatened just as much as any other living organism's. We must understand the natural system so that we can live with it and in it and use it without destroying its intricate balance. While much emphasis currently is given to deriving food from the sea, students with a real understanding of life in the ocean will appreciate that marine biology is concerned with matters far more important than the harvesting of more protein. For example, life processes generate (and consume) oxygen, maintaining the atmospheric oxygen at its present, beneficial level. The role of the living system in the maintenance of the life supporting quality of our air is obviously as important as food production. Stated simply, mankind needs to understand the nature of the living system of the oceans so that society can be a prudent custodian rather than a destructive exploiter of the remarkable web of life that exists in the sea. Lest you think this is an unrealistic goal, consider the achievements of our farmers. A modern farm can be as productive 100 years from now as it is today because farmers have learned to be custodians of the soil rather than exploiters. Knowledge of the cycles of air, water, and fertilizer allows a farmer to protect rather than exhaust his resources. The sea is bigger and more difficult to understand than a land system such as a farm, but the size and complexity of the system increases our need to understand and preserve the system.

The ideas of marine biology are exciting and engaging; how can they be otherwise when we are talking about restless, huge oceans and the fascinating plants and animals that live in the sea? But scientists frequently express these ideas in rather dull, colorless language. Scientists use abstract language so that they can make their ideas apply to many examples. We say organisms require energy to live; this is an accurate statement and a good way to introduce a discussion about the food chain or energy dynamics of the sea. But perhaps we can engage you students in the excitement we scientists feel by expressing the same idea in more graphic and less abstract terms. Consider for a moment a young blue whale swimming through the cold, grey Antarctic sea; the whale is three years old, sixty feet long, weighs fifty tons, and is swimming at a speed of 12 miles an hour. Obviously it took a lot of food to grow fifty tons of whale in three years, and just as obviously it takes a lot of fuel to supply the energy to drive the huge animal through the water. What is the energy supplying fuel, where does it come from, and how can a young whale gather enough to support himself; and finally where does the energy ultimately go? The answers to these questions make up the subject of food chain dynamics.

Food has two important components. One component is the matter which makes up the food, that is, the actual atoms of carbon, oxygen, hydrogen, nitrogen, phosphorus, and iron. The atoms can be visualized as the structural material or building blocks from which a living system can be built. In building something, energy is required to organize and assemble the structural material. The second component of food is chemical energy which exists in bonds between the atoms that make up the food.

The energy that the young blue whale uses to swim through the Antarctic sea originates in thermonuclear reactions that occur in our sun. The nuclear fusion of hydrogen atoms into helium releases huge amounts of energy some of which eventually reaches our planet in the form of radiant energy or sunlight. The energy of the sun is absorbed by green plants and converted into chemical energy by the process known as photosynthesis.

The photosynthesis of marine plants is exactly the same as that of the familiar land plants such as grass or trees. Light energy, absorbed by chlorophyll, becomes chemical energy in the form of excited chlorophyll electrons. In subsequent reactions the excited electrons are involved in the synthesis of carbon dioxide and water into an energy rich material called carbohydrate. The carbohydrate can be processed by plants and animals into proteins and fats and thereby used to build the elaborate structural material necessary for the construction of living systems. Carbohydrate can also be broken down, or metabolized, by organisms with the subsequent release of carbon dioxide, water, and the covalent bond energy. The liberated energy is then available to the living system for the assembly of new kinds of molecules, or for mechanical work such as muscle contraction, or for any of the other energy requiring reactions that the cellular machinery carries out.

The energy containing carbon compounds that we know as carbohydrates, fats, and proteins belong to a general class of compounds called organic compounds. The photosynthetic production of organic material is frequently called organic production or primary production and the organisms that carry on this process are referred to as primary producers.

The essence of photosynthesis, or primary production, is that it is the process by which the solar energy is made available to the living system. All organisms are ultimately dependent on the chlorophyll containing plants, for only those plants can trap the energy and "package" it into organic molecules which can be used by other organisms as a supply of energy. Obviously the amount of energy processed by the primary producers sets an absolute upper limit on the number of dependent organisms or consumers that can exist in the system. We can deduce, then, that since our blue whale is able to grow very rapidly, a large number of primary producers must be present in the sea where the whale lives.

At this point we should leave our blue whale and look in detail at the plants and animals that make up an ocean food chain. After we are more familiar with the nature of the living system, we can return to our question about how can a whale gather or collect enough of the sun's energy to support itself. We know that plants trap the energy, now let us look at the route of the energy or food from the plant on up the food chain. To do this we must learn more about the organisms themselves. Animals and plants that live in the sea have three possible modes of life available to them and it is very useful to be able to distinguish between the three ways of life. They can float passively in the water, they can swim actively, or they can live on the bottom. The drifters are called plankton, a word taken from Greek which means "that which is made to wander or drift." The active swimmers such as fish and whales are called nekton, and bottom dwelling plants and animals are referred to as benthos. The plankton community is divided into the photosynthetic, or plant plankton, which are called phytoplankton, and the animal plankton, or zooplankton.

Phytoplankton, the primary producers of the open sea, are microscopic, single-celled algae. Within their single cell they carry on all the different functions that land plants perform with their complex system of roots, stems, leaves and flowers. The small size of phytoplankton is an adaptation to the conditions that a planktonic plant faces. The smaller an object is the larger is its surface area in relation to its volume or mass.

The large surface to volume ratio has at least three benefits for phytoplankton that we can understand. Firstly, the large surface area creates frictional resistance with the water and retards sinking. We know that an intact brick will sink faster than the same brick ground into dust. Secondly, the large surface area provides a large area for the uptake of raw materials for photosynthesis, and third, the large surface to volume relationship increases the amount of light that can be absorbed.

Of the various kinds of plants that make up the tiny unicellular phytoplankton, three groups are by far the most abundant and numerous. These are the diatoms, dinoflagellates, and coccolithophores (see Figure 1). Diatoms differ from all other plants in having a cell wall which deposits an external skeleton of silicate which encloses the cell like a glass box. The siliceous skeleton is in two parts which fit together like an old-fashioned pill box. Electron microscope pictures have revealed that the siliceous walls of diatoms are very elaborate structures composed of intricate patterns; each species of diatom has a different and characteristic pattern of pits, striations (or channels), and perforations. Diatoms are able to multiply very rapidly; under favorable conditions the population doubles in less than one day.

Diatoms are non-motile, completely at the mercy of ocean currents and gravity; but the other major groups of phytoplankton, the dinoflagellates and the coccolithophorids, possess flagella and are capable of some movement through the water. Dinoflagellates possess two flagella which lie in grooves in their rigid cellulose cell walls. Some dinoflagellates have a light-sensitive eye-spot or stigma which enables them to move in relation to a light source.

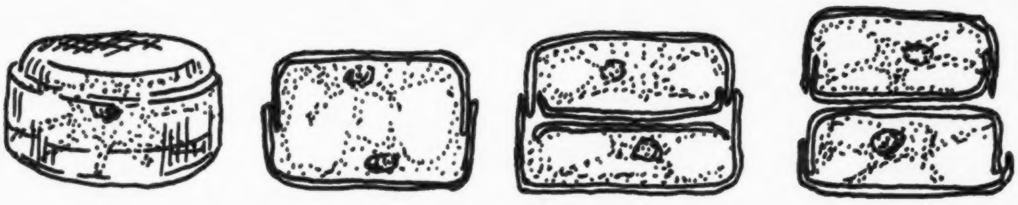
Coccolithophores also possess two flagella on each cell, but they differ from dinoflagellates in that each cell is protected by many tiny plates of calcium carbonate.

The three groups of phytoplankton are similar in that they all are capable of photosynthesis and they all, therefore, are referred to as the primary producers of the marine food chain; but the important differences should be recognized also. Each group has evolved a tough external capsule of a different material: diatoms use silicate, dinoflagellates use cellulose, and coccolithophores use calcimm carbonate. The external skeletons of dead diatoms and coccolithophores sink and become incorporated in the deep sea sediments, thereby leaving a detailed geologic record of their past abundance and distribution in the earth's oceans. Diatoms store organic material in the form of fat drops inside the cell; geologists speculate that our oil reserves may have originated in diatoms.

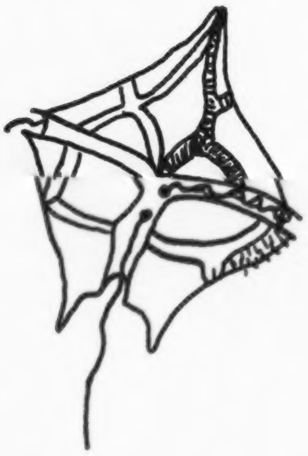
Each of the major groups of phytoplankton is best adapted to a different set of environmental conditions. Nutrient rich conditions are found in the springtime in regions of the ocean where deep waters are brought to the surface by upwelling. Diatoms are by far the most abundant kind of phytoplankton in the spring or upwelling blooms; we believe this is because diatoms are able to grow faster than dinoflagellates or coccolithophores in a nutrient rich environment. Coccolithophores, on the other hand, are able to live and grow in nutrient poor situations, therefore they are the most abundant group in the low nutrient torpical seas. In rough analogy with land plants, we could call coccolithophores "desert" plants since they can survive in conditions which are too harsh for other phytoplankton. Dinoflagellates have the ability to grow well under a variety of environmental conditions, We might generalize and say that they can exploit a wide variety of conditions, but they are most abundant between the extremely rich situations where diatoms are predominate and the poor conditions where coccolithophores predominate.

The phytoplankton are "grazed" or consumed by the herbivores or intermediate levels of the marine food chain. Since the phytoplankton are small the animals that have evolved the ability to harvest the unicellular plants must also be small. A generalization we can make about food chains is that each organism eats something smaller than itself. Therefore, the organisms that consume the microscopic phytoplankton are smaller than grass-eating land animals.

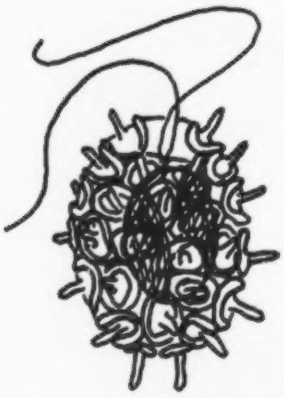
Among the most successful phytoplankton harvesters are members of the zooplankton called copepods. Copepods are small crustacea which are about 1/4 inch or less in length and which swim by means of two oar-like



a. Diatom undergoing division of cell



b. Dinoflagellate



c. Coccolithophore

Fig. 1. Three common members of the phytoplankton. (1a from Alister C. Hardy, reproduced with permission; 1b from M. U. Lebour; 1c from John E.G. Raymont, reproduced with permission.)

appendages. (Their name, copepod, means oar-footed.) It has been suggested by the English oceanographer Sir Alister Hardy that the number of individual copepods in the world's oceans exceeds the number of any other group of multicellular animals. The herbivorous copepods have fan-like appendages bordering their mouths. Water is drawn toward the mouth by beating these appendages at a high rate, often up to 60 strokes per second. The small whirlpools that are created pass through sieve-like structures which filter out the phytoplankton. When a large portion of filtered material has accumulated, other appendages convey the concentrated mass to the mouth.

While there are numerous other kinds of plant eating zooplankton, copepods are good organisms to use as representatives, because they are quantitatively the most important marine herbivores. Copepods, like many of the planktonic animals, have a complex life history that involves several different stages (see Figure 2). The first stage is a characteristic larval form called a nauplius.

The nauplius, as it hatches out of the eggs carried on the abdomen of the female copepod, is a tiny, six-legged, kite-shaped animal. It possesses a single eye and a protective armor of chitin, the same material that insects use in the construction of their external skeleton. As in all organisms with rigid exoskeletons, the copepod nauplius cannot grow continuously but must grow discontinuously in a series of short steps. The old exoskeleton is shed or "molted," and the copepod grows very rapidly in the short interval before the new exskeleton hardens. Each species of copepod goes through a definite number of molts during its life, with growth and some change in its body form occurring at each molt. The adult form, in which mating and reproduction occur, is the eleventh or twelfth stage in the series. The larval copepods, like the adults, are filter feeders which eat phytoplankton that are strained out of seawater by seive-like mechanisms.

Copepods produce three or four generations per year so that they can reproduce fast enough to harvest efficiently the rapidly growing phytoplankton populations. The copepods and other herbivorous zooplankton are eaten by fish or by bigger zooplankton. The copepod eaters are referred to as predators, carnivores, and secondary consumers, meaning they prey on other animals, they eat meat, and they are the second level of donsumers in the marine food chain. Figure 3 shows that the food relations of a fish such as a herring are complex, but we can see that the sun's energy that was captured by photosynthesis is passed from phytoplankton to copepod to herring, then to a still larger higher predator such as a tuna, squid, porpoise, striped bass, or even man.

Herring and other zooplankton-eating fish have a remarkable food capturing mechanism. If you look at the gills on these fish, you can see that the gill supports or gill arches have a fringe of stiff strainers which are called gill rakers. The gill rakers form a fairly rigid mesh through which the water that enters the fish's mouth must pass. Any objects in the water stream that are larger than the mesh size are filtered out and retained on the rakers. As the fishs grow and the mesh size of the gill raker grid increases, the fish harvests different size zooplankton but retains the same basic feeding mechanism.

The diatom, copepod, herring, squid, striped bass, man food chain is a familiar one that we can observe in our nearby waters and one that we are a part of in a very real sense. By comparing this food chain with the one to which the Antarctic blue whale belongs we can become aware of the economics or bookkeeping underlying the passage of energy and matter through a living system. The dominant property of such transfer systems is that nine-tenths of the energy and matter is lost to the system with each transfer. It is really incorrect to view the decrease as a loss of anything; it is simply that a copepod uses nine-tenths of everything he takes in to maintain himself and "saves" one-tenth in the form of the growth of new copepod mass. The implications of the nine-tenths cost of maintaining each transfer step in a food chain are far reaching. We can calculate roughly that one pound of man was produced from 10 pounds of bass, which required 100 pounds of squid, which required 1000 pounds of herring, which required 10,000 pounds of copepods, which required 100,000 pounds or

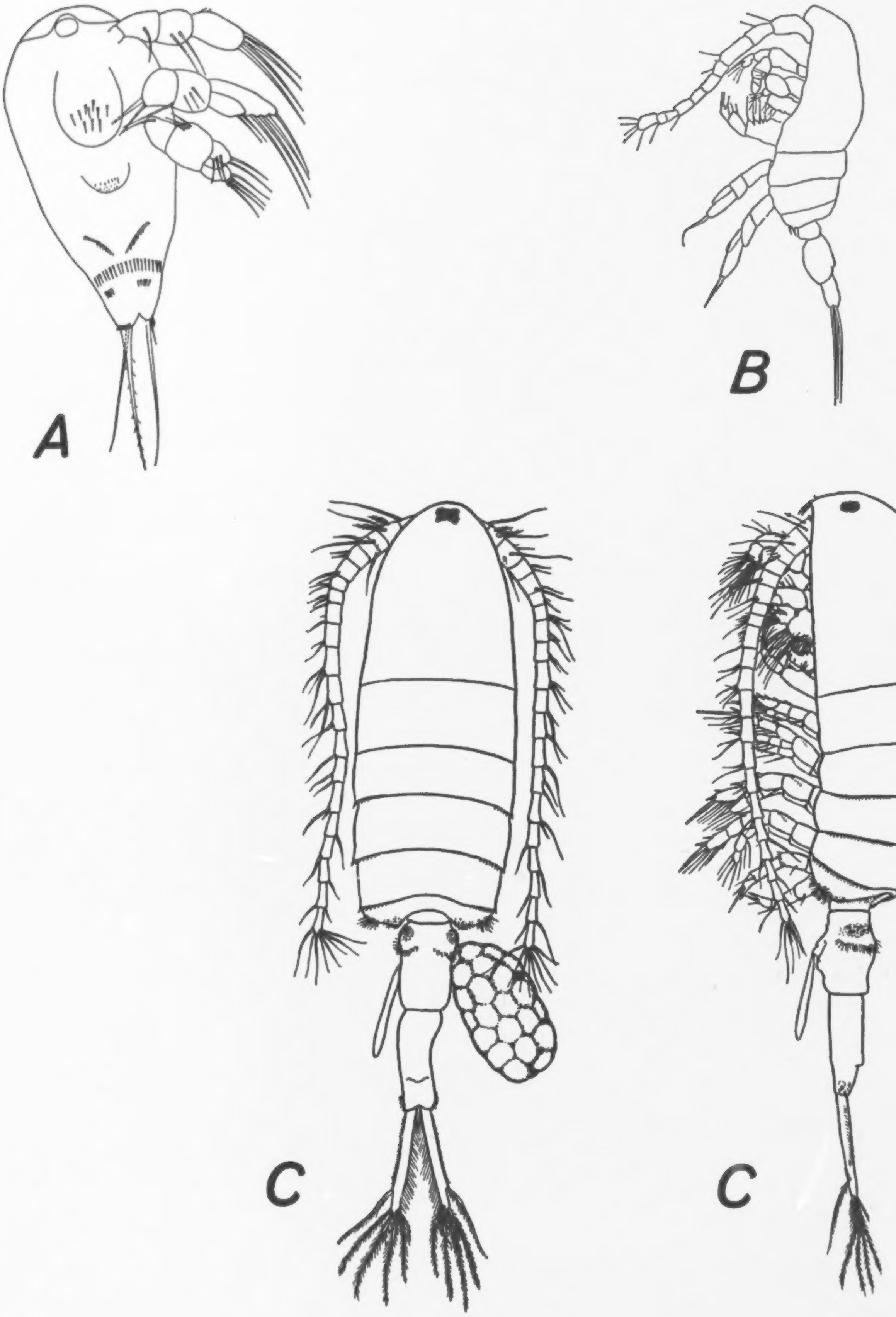


Fig. 2. Copepod (Pseudodiaptomus sp.) a, a nauplius stage; b, a copepodid stage; c, adult stage. (2a and 2b from George D. Grice; 2c from M. W. Johnson.)

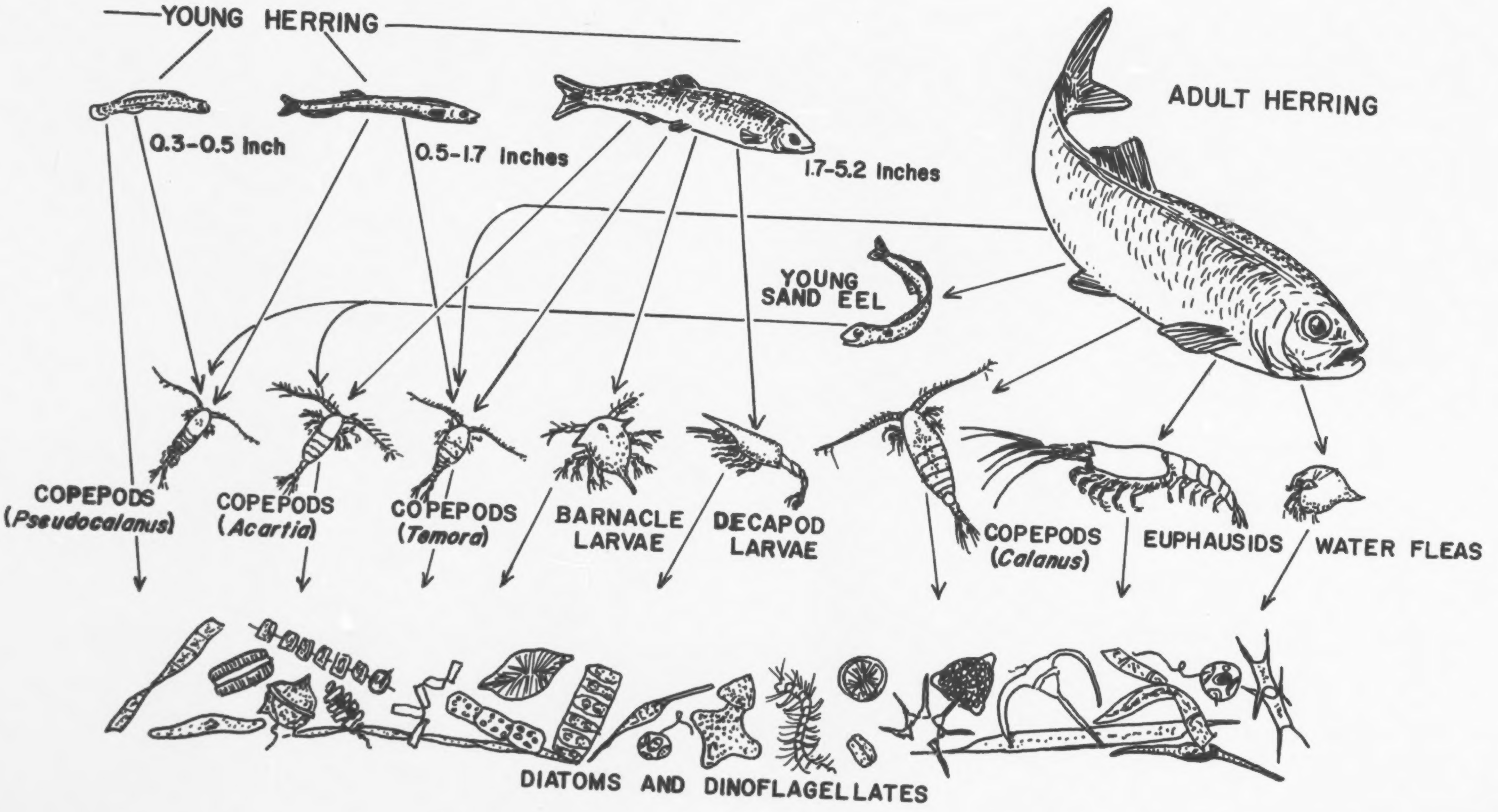

YOUNG HERRING
0.3-0.5 Inch
0.5-1.7 Inches
1.7-5.2 Inches
ADULT HERRING
YOUNG SAND EEL
COPEPODS (*Pseudocalanus*)
COPEPODS (*Acartia*)
COPEPODS (*Temora*)
BARNACLE LARVAE
DECAPOD LARVAE
COPEPODS (*Calanus*)
EUPHAUSIDS
WATER FLEAS
DIATOMS AND DINOFLAGELLATES

Fig. 3. Herring food chain. (Adapted from Alister C. Hardy.)

50 tons of diatoms. The Antarctic blue whales use the phytoplankton more efficiently because they belong to a shorter food chain that lacks the intermediate steps found in the herring chain. The blue whales eat krill, a two inch shrimp-like crustacean that grazes on diatoms just as copepods do. Therefore, the complete chain consists of diatoms, krill, and the whale. Using the same mathematics as before, one pound of whale represents 10 pounds of krill which represents 100 pounds of diatoms. The two food chains can be further compared by observing that starting with 50 tons of diatoms one could get 10 pounds of striped bass or one-half ton, 1000 pounds, of whale depending on the kind of biological system carrying out the transfer.

We should emphasize that the blue whale-krill-diatom system is probably the most efficient food chain that has ever evolved on earth. The blue whale is the largest creature that has ever lived and has the highest growth rate.

The good student should ask at this point if short food chains are more efficient; furthermore, if the relentless pressure of natural selection is always operating, then why has not evolution produced more short food chains? The answer can be found in a close examination of two food chains. The krill which the blue whale consumes is a single species called Euphausia superba and the diatoms consumed by the krill consist of members of one restricted group or genus of diatoms. Compare this exceptional degree of specialization with the condition found in a herring food chain. Note that an adult herring consumes a variety of kinds of zooplankton and as the herring matures the kinds of organisms that it consumes change. Consider which ecological plan is "safer." You appreciate that the blue whale food chain while highly efficient is also evolutionarily unsafe. These whales depend on a single kind of food organism throughout their lives; if the krill became extinct or reduced in numbers for any reason the blue whales would also become extinct.

On the other hand the disappearance of any single species from the herring food web would not destroy the whole food chain. Such a system has duplicate or multiple channels through which the energy is passed. Such systems do not have the spectuacular efficiency that produces 70 foot whales but they have long term evolutionary security; that is, they are less likely to become extinct. The food chains that we observe in the sea today are evolution's workable compromises between efficiency and evolutionary security.

Benthos

The benthos consists of the plants and animals that are associated with the bottom of the sea rather than exclusively with the water as the plankton and nekton are. The bottom community contains large attached algae, many kinds of microbes and a very great variety of invertebrate animals. The large attached algae, frequently referred to as seaweeds, are the common plants that can be seen covering rocks at low tide. These algae are restricted to the relatively shallow, near-shore parts of the ocean where sufficient sunlight can penetrate to allow photosynthesis to occur. In shallow waters the photosynthesis carried on by benthonic algae does contribute to the food supply which becomes available to the benthonic animals. However, the amount of food produced by benthonic algae is small in comparison with that produced by the phytoplankton. The benthonic animals depend in large part, as do the zooplankton and nketon, on the food produced by the tiny phytoplankton that grow in surface waters. The large seaweeds do provide a source of cover and protection and therefore contribute greatly to the richness of the community. The relative lack of importance of the seaweeds as a food source and their great importance as cover was discovered when men found that fish and invertebrates would settle and grow in clumps of plastic seaweed. Great mats of plastic fronds were placed on the sea floor to stop the movement of sand. Within weeks a rich and varied benthonic community had moved into the plastic seaweed, apparently attracted and held by the cover and protection. To describe this in more formal words we can say that the animals in this situation were habitat not food limited.

What they needed was a place to live just as a rabbit needs a briar patch. One of the exciting things that man can do in the sea is to provide habitat and thereby greatly increase the richness of the benthos in shallow water areas.

The benthonic plants are, of course, limited to the shallow ocean floor where enough sunlight can penetrate to permit photosynthesis. Benthonic animals are present and have been caught and observed on all parts of the ocean floor including the deepest trenches. The animals that live on the deep ocean bottom, far removed from the primary production step of the food chain, are able to survive because a small portion of the organic matter produced in the sunlit zone is eventually distributed to all parts of the deep ocean floor. In the unvarying cold and perpetual dark of the deep sea an amazing variety and abundance of animals have been found. The study of the deep sea benthos is the last exciting frontier is descriptive biology that exists in marine biology.

Vertical Migration and Bioluminescence

The preceding information attempts to describe some of the things that we know about the biology of the sea. It is important that a student recognize that a great body of knowledge about the sea exists, but it is more important to understand that the excitement of science is in the things we do not know. The subject matter of science, that is the things scientists are concerned with right now, are the things we do not know. Two large areas of marine biology that are very poorly understood are the vertical migration of plankton and the bioluminescence of marine organisms.

Vertical migration

Vertical migration is the name given to the peculiar vertical movements of plankton; the movements are towards the surface at night, away from the surface into deeper water during the daytime. The "migration" is a daily one with animals making one roundtrip each day and should not be confused with the seasonal, long-distance movements of animals that are usually referred to as migrations. The extensive vertical movements made by marine organisms have been known since the earliest days of marine biology because naturalists noticed that plankton nets took larger catches when towed in the surface waters at night. While marine biologists were aware of vertical migration, no one suspected how widespread and deep the migrations were until echo sounders began to be used in the deep ocean during World War II. An echo sounder is an instrument that measures the length of time necessary for a sound to travel from the ship to the bottom and back to the ship. The sounder times the bottom echo, and since the travel time of the echo is proportional to the distance of the ship from the bottom, the echo sounder can give a reading of depth directly. During the wartime work on submarine detection by echo location, scientists found that layers of echo-producing objects, or sound scattering agents, were consistently present in the ocean. These layers came to be called the deep scattering layers. As scientists learned to follow the movements of the deep scattering layers , an exciting drama unfolded. The scattering layers were found throughout the world's oceans from the equator to the northern latitudes, and most of the layers carried out a daily vertical movement going from the surface at night to depths of 200 to 600 meters during the day. The echo soundings showed marine biologists that vertical migrations were far more important and widespread than had been suspected.

Much research has been done on the deep scattering layers, and the general problem of vertical movements in the sea and the status of this work will show a student the kind of work that tomorrow's scientist must do. Using very elaborate and expensive electronic and sound equipment together with nets and the deep submersible submarines, we have definitely identified the kinds of animals that make up the sound scattering layers. The organisms that make good solid echos are those with air-filled bladders or floats, and two kinds have been associated with the layers' deep sea fishes (especially lantern fish and hatchet fish) and certain kinds of jellyfish called siphonophores. Another aspect of the layers that must be emphasized is that different kinds of lantern fish and siphonores make up the layers in different parts of the ocean. The layers look alike on an echo sounder, but when biologists have observed them from submarines in different parts of the ocean, they have noted that the specific kinds of animals and the proportions of different kinds are quite different. In addition to knowing what animals are present in layers, we also know that the migrations are regulated by light. Studies of the movements as the day length changed in the polar latitudes show that the migrations follow the light intensity precisely. Most impressive, however, was a study where the layers were followed during an eclipse of the sun. The animals started towards the surface as the eclipse began even though it was high noon. Scientists know reasonably well what animals are present in the vertically migrating layers and they know that the animals' behavior is regulated by the light intensity. Now you must ask what is the biological function of vertical migration? The great vertical movements use up so much energy, and the behavior has evolved in so many different kinds of animals that we must suspect that vertical migration plays a very important role in the survival of animals in the marine world. Many ideas have been advanced to explain the biological significance of vertical migration, but no explanation is really convincing. Using your knowledge of currents, temperatures, phytoplankton distribution, and food chains, you should be able to put together some ideas yourself. Today's student should be aware that many of our concepts about how the sea works are uncertain or non-existent. We know what is there, and we know in some cases how physical or biological processes occur, but we frequently don't know how the whole works together. Explaining the ecological significance of vertical migration is a good example of where tomorrow's scientist will have to put together a mass of separated physical and biological information that today's scientist has gathered.

Bioluminescence

Bioluminescence is the production of light by living organisms. In the sea, many kinds of organisms from bacteria through fish produce bioluminescence. During a dark night at sea the wake of a ship may be outlined in blue light if it passes through water containing a swarm of bioluminescent organisms. It is a dazzling show of light when the bow wave becomes a brilliant cascade and the propeller is outlined in blue. The organisms most often producing these bright displays are members of the phyotplankton called dinoflagellates. The tiny dinoflagellates produce a flash of light when they are distrubed by turbulence from a ship or any object causing a disburbence. If you dip up a glass of water containing the blue light and carefully pour out part of the water until you have only a single source of light when the glass is shaken, you can then examine the contents of the glass under an electric light and see that there is nothing visible in the water. The tiny dinoflagellates are, of course, almost invisible without a microscope, but each small cell is able to produce a flash of light that is clearly visible at night from a distance of several yards.

Man has been fascinated by bioluminescence ever since the first sailors ventured out; considering the strangeness of the blue light it is surprising that early seamen did not have more myths and tales about bioluminescence. Benjamin Franklin noted the light during his Atlantic crossings when he charted the Gulf Stream. He thought at first that the light was produced by an electrical reaction occurring between the water and the salt it contained. When he found that sea water which had been kept in a jar for some time stopped emitting light, Franklin gave up his electrical hypothesis because he knew that the water and the salt had not changed and, therefore, that the light producing ability must not be dependent on thosecharacteristics. Today we know that the explanation for Franklin's experiment is simply that the tiny dinoflagellates died in the jar and therefore light production stopped. You can imagine how difficult it would have been for someone in Ben Franklin's time to accept that an invisible organism could produce such an impressive sparkle, and, of course, at that time the presence of microscopic plankton was not suspected in seawater so Franklin would have no basis to suspect that a tiny living agent was producing the light.

Dinoflagellates, while they are the most bioluminescent organisms, are by no means the only ones. There are light prodcuing bacteria as well as jellyfish, shrimp, copepods, many kinds of marine worms, and many kinds of marine fish. The light producing capability has arisen and been maintained in many different and unrelated kinds of organisms. Some basic characteristics like the presence of a backbone are traceable through a line of related organisms; biologists describe this situation by saying that the presence of a backbone evolved only once and was passed through evolution to a great family of related animals. Bioluminescence is distributed among living forms in a very different pattern; biologists believe that the ability to produce light evolved independently many times during the long history of life.

Marine Microbiology

Marine microbiology is the study of the small, single-celled organisms that live in the sea. These tiny entities can be seen only under a microscope and are commonly referred to as micro-organisms. The micro-organisms that live in the sea can be divided into two large but functionally distinct groups: the single-celled plants, or phytoplankton, that we have discussed already and the micro-organisms called mineralizers or decomposers which consist mostly of bacteria. The phytoplankton, because of their role as the food manufacturers in the food chain, are considered separately from the bacteria. Both groups, phytoplankton and bacteria, are micro-organisms; but since the functions of the two groups are different in nature, it is logical to discuss them separately. To get a quick feel for the functional differences of the groups, remember that phytoplankton use the sun's energy to make organic matter out of carbon dioxide and water, whereas bacteria break down organic matter converting it back to carbon dioxide and water and releasing the energy. It should now be clear why the phytoplankton are called producers and the bacteria are called decomposers. A point that must be emphasized here is that the decomposers are just as important to the cycle of life in the sea as the producers are. If the organic material synthesized by plants were not being constantly decomposed back to CO_2 and H_2O, then the raw materials for new life would not be available and the living cycle would stop. It is important to understand that all the "parts" of a living system are essential to the working of the system and that no one part of the cycle can be called more important than another.

The phytoplankton float freely in seawater, but bacteria grow best on surfaces. The surfaces may be the air-sea interface where air and water meet, the bottom where sediment and water meet, or the surface of any particle that exists in seawater. The number of bacteria or the size of the population is controlled by the amount of food and the availability of surfaces for the bacteria to grow on. Most often the surface and the food supply are the same item. For example, a dead diatom rapidly becomes coated with a film of slime. The slime is made up of millions of rapidly growing and dividing bacteria. Between meals, that is, after one food source is consumed and before a new source becomes available, bacteria exist in seawater as resistant resting cells. These cells function like the spores or even seeds of other organisms in that they provide a mechanism for being ready to exploit favorable growing conditions. The metabolism of the resting cells is greatly reduced, almost nonexistent; therefore, these cells can persist for long periods of time without a new food supply, and yet they are ready to begin growth and division as soon as a food source becomes available. Resting bacterial cells of many kinds are present everywhere in the sea; from any water sample an amazing number of bacteria can be grown if a variety of food sources is supplied.

You can prove to yourself that decomposing bacteria are present as resting cells in any natural waters by filling a sterilized bottle containing a hot dog with water from any river or bay. If you carefully sterilize a bottle with a hot dog in it, then open the bottle under water and seal it after filling under water, any bacteria in the bottle will have entered with the water. If there are decomposing bacteria in the water, the water will become cloudy, and in a week you will notice a very strong smell when you open the bottle. The smell is from products that are produced by the bacteria as they break down the protein contained in the hot dog.

So far we have referred to the decomposing micro-organisms as bacteria. This is more or less accurate, because bacteria are responsible for most of the microbial decomposing activity; but in addition to bacteria, there are also marine fungi, yeasts, protozoans, and viruses.

The activities of the marine micro-organisms have little visible impact on man and his interests except perhaps in the area of biodeterioration of metals, plastics, and wood products. However, the indirect impact of microbial activity on man is extremely important. If we want clean and healthy air and water, we need a healthy sea, and a healthy sea is one in which all the units of the living system are functioning. Man puts a load on the functioning system by using the sea as a giant and limitless waste disposal system. Massive waste disposal operations are an absolutely necessary feature of the social system man lives in, but waste disposal is such an intellectually unpleasant topic that most of us would rather not think about it. However, the time whem we had the luxury of not thinking about waste disposal is past. Few people now live on farms, but anyone who grew up on such a farm knows that a healthy cesspool very effectively decomposes sewage by means of bacterial breakdown. The sewage is decomposed to carbon dioxide, nitrates, phosphates, and other basic constituents including water. The water percolates through the soil and eventually can re-enter the farm well where it is used again as pure, good-tasting drinking water. If man intends to use the sea as a waste disposal system, he must start thinking about and caring for the marine environment in the way a cesspool is cared for. Like a family cesspool, the marine system must not be overloaded; that is, wastes must not be put into the system faster than they can be broken down. Even more ctirical is the problem of toxic materials that will harm bacteria. Detergents, toxic metals, acids, petroleum products, pesticides, or any of the toxic byproducts of our industries can inhibit or prevent bacterial activity, thereby preventing effective breakdown of organic wastes.

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4

11. THE ORIGIN AND DEVELOPMENT OF LIFE IN THE SEAS

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The Origin of Life

The question of the origin and evolution of life is the oldest and most elusive problem that philosophers and scientists have tried to solve. For 25 centuries, since the beginnings of Greek science, men have struggled to find a rational and convincing explanation of how life began. One of the glories of being alive at the present time is that we can have at least a partial understanding of the origin of life. The student of today can know more about how life began that the most educated scientist could know fifty years ago.

The living systems we are familiar with here on Earth require liquid water; water is the most abundant constituent in a living unit. It serves as a solvent for many of the other constituents of living systems, and it contributes to the structure of many essential biological molecules by forming coordinate bonds and bridges with the molecules. Water, therefore, plays a dual role in living systems, being both the solvent that makes diffusion and dispersal possible and the cement that stabilizes the large elaborate molecules.

Scientists now think that water and other volatile components of the Earth's original atmosphere, such as methane and ammonia, were released from molten rock in the Earth's interior at some time after the Earth had assumed its present shape. The process of release of the water vapor and other volatiles is called degassing and is the same process that occurs when a bottle of carbonated drink is opened. The carbon dioxide degasses from the drink and enters the atmosphere. Although scientists agree that degassing of the molten interior is the source of the water, there is no agreement about the time scale over which the degassing has occurred. It is possible that most of the water was released early in the evolution of the Earth, creating the primitive atmosphere and oceans in a single event; or the degassing could be a continuous process by which water was added slowly to the Earth's surface and is still being added by volcanic action. If the degassing is a continuous process, then the amount of water in the oceans is constantly increasing, and we might expect to see a consistent pattern of change in the sea level over periods of geologic time. Unfortunately, this is not true because of the many factors affecting the sea level which are independent of the volume of water in the ocean basin. However, despite our inability to know what the actual time course of the filling of the ocean basins was, i.e., whether they filled in a single early event or gradually over a long period of time, we can be sure that the young Earth had some water vapor in its atmosphere and liquid water on its surface. In addition to water vapor, the primitive Earth atmosphere contained hydrogen, methane, and ammonia.

A great advance in our understanding of how life began was made in 1953 by a student named S. L. Miller. He demonstrated that organic compounds identical to those that make up living systems are synthesized when a mixture of simple gases is subjected to a spark discharge. The significance of Miller's work is that he showed that some organic compounds are always formed when a gas mixture like the primitive atmosphere (water vapor, ammonia, methane, and hydrogen) is subjected to an electrical discharge similar to a lightning discharge. The apparatus with which Miller made this discovery is shown in Figure 1. In the system methane, water vapor, ammonia and hydrogen circulate past sparking tungsten electrodes. The water vapor is produced by boiling water in the flask at the lower left and the vapor is condensed by the cooling jacket just below the spark chamber. The U-tube at the base taps the condensed liquid and promotes a clockwise circulation of the mixture. When the mixture was cycled for a week the condensed liquid became dark red and cloudy. Chemical analysis of the condensed material showed that a mixture of amino acids and other organic molecules had been synthesized.

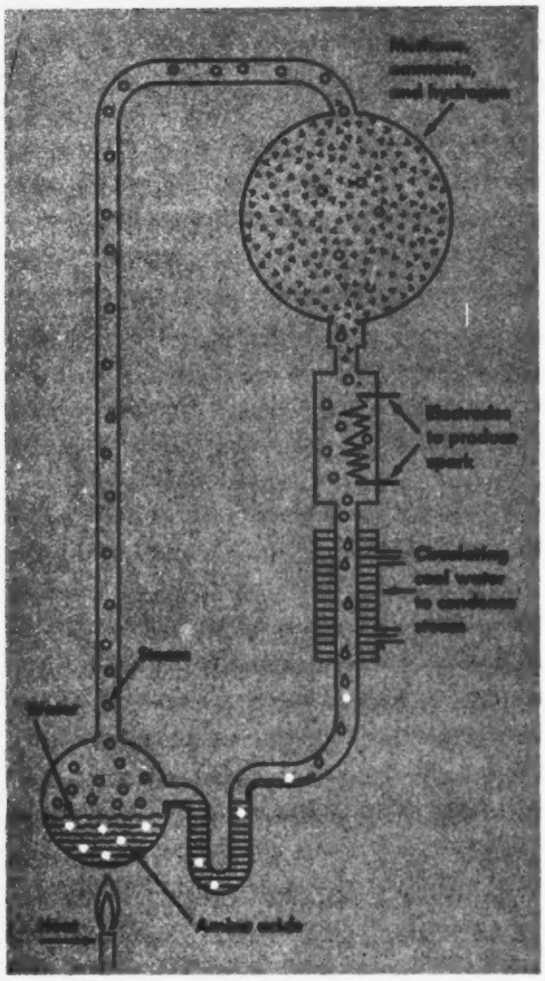

Methane, ammonia, and hydrogen
Electrodes to produce spark
Circulating cool water to condense steam
Steam
Water
Heat
Amino acids

Fig. 1. S. L. Miller's apparatus for producing amino acids under primitive Earth conditions (redrawn from Miller). Steam was passed through a mixture of gaseous methane (CH_4), ammonia (NH_s), and hydrogen (H_2), and then exposed to a high-energy electric spark before being recondensed as water. After a week of operation of the apparatus, the water was found to contain amino acids, the fundamental building blocks of proteins and organisms. (From A. Lee McAlester.)

Miller's work encouraged other scientists to perform similar experiments using various gas mixtures and the various energy sources that could have been present on the primitive Earth. Among energy sources used to simulate primitive energy sources have been ultraviolet light, high temperature, high pressure, ballistic missile impact, gamma irradiation, sunlight and silent electric discharge. These experiments have succeded in synthesizing all of the constituents of living systems. The ribose and deoxyribose sugars which provide the backbone for the genetic macromolecules, RNA and DNA, were first synthesized in dilute salt water indicating that the primitive ocean probably played a large role in the synthesis of the original organic material.

The intellectual momentum developed by these experiments has continued right to the present. Frequently we read in the current scientific literature that by various manipulations of the experimental conditions (rapid cyclic heating and cooling, for example) scientists are able to get organic molecules to polymerize into macromolecules or to get macromolecules to aggregate into discrete spheres. Thus the origin of a living system by gradual chemical evolution of a non-living system is an idea whose feasibility has been demonstrated.

It is still difficult to understand how a self-replicating organism evolved from the static organic units that abounded in the primitive ocean. Many scientists are proposing ideas to explain this step, and we can expect that experimental evidence will soon be available to indicate how the transformation occurred.

The original organisms had an abundant food supply in the waters from which they arose. The waters of the early lakes and oceans are described as being a dilute organic soup because of the accumulation of amino acids, carbohydrates, fats and proteins over eons of time. As the primitive organisms consumed the food available in the organic soup, natural selection favored the survival of organisms that could carry out the synthesis of complex molecules from simpler molecules. Eventually the process we know as photosynthesis arose and provided a powerful survival advantage insuring that life would survive even after the original

soup had been consumed. Photosynthesis is the process in which light energy is used by green plants to synthesize complex molecules from carbon dioxide and water. Remember that the process discovered by Miller in 1953 was the synthesis of complex molecules from simple gases using electrical or ultraviolet energy. The evolution of photosynthesis consisted of a living system developing the ability to carry out a "Miller synthesis" within itself in a highly organized and regulated manner. The reaction system shown in Figure 1 was replaced within the cell by the chloroplast with its chlorophyll and enzymes performing the synthesis in a manner thousands of times more efficient than Miller's system. It is impressive to understand that even a process as complex as photosynthesis is a logical modification of a process that will occur in the absence of living systems. This kind of evidence shows that living systems, while vastly more complex than non-living are not fundamentally different. This idea has been expressed in more formal terms in the doctrine of uniformitarianism. This doctrine states that the fundamental properties of the universe, such as the way matter and energy interact, have not changed during the evolution of our planet and universe. The fundamental characteristics of the universe are independent of time; therefore, new processes such as life are subject to the same physical and chemical principles that regulate the non-living world.

The atmosphere of the primitive Earth did not contain oxygen; therefore the earliest organisms had to obtain energy from their food (the organic soup) by a non-oxygen requiring breakdown of the food material. The release of energy from food without the consumption of oxygen is called anaerobic respiration or fermentation. Many microorganisms that are alive at the present time are capable of only anaerobic respiration and, therefore, can exist only in environments isolated from our current oxygen-containing atmosphere. Most organisms, including ourselves, are capable of limited anaerobic respiration but depend on aerobic respiration to supply energy. Our limited anaerobic respiratory ability can be viewed as a biochemical legacy from the time when life existed in the primitive anaerobic atmosphere. As the organic soup was consumed and selection favored the survival of photosynthetic organisms, a global change in the chemical makeup of the Earth's atmosphere began to occur.

The photosynthetic process releases oxygen as a waste product during the synthesis of new organic material so that as the early algae developed and became the most abundant organisms in the early oceans, the atmosphere was enriched with oxygen. With the accumulation of photosynthetic oxygen in the atmosphere and accumulation of food in the form of the algae, the evolution of animals with aerobic respiration became possible. Aerobic respiration is the process in which the organic material of food is combined with oxygen, thereby releasing energy, carbon dioxide, and water. Since carbon dioxide is a raw material in photosynthesis and a waste product of aerobic respiration and oxygen is a waste product of photosynthesis and a raw material for aerobic respiration, we can see that the two processes going on simultaneously would establish and maintain a steady state of carbon dioxide and oxygen in the Earth's atmosphere.

From the time when the atmosphere attained its present oxygen concentration and aerobic respiration was fully developed to the present time the basic chemistry of living systems has changed very little and a phase of structural evolution has taken place. The molecular biology of our cells is essentially the same as the molecular biology of bacteria or blue-green algae, but our biochemical components are assembled in a vastly more complex system of cell organelles, cells, and organs. A graphic summary of the stages in the development of life from non-living matter is given in Figure 2.

The Development of Life in the Seas

Our ideas about the origin of life are based on information from many sources, such as astronomical studies on the atmospheres of other planets and experimental chemical studies which try to simulate conditions on the primitive Earth. These sources of information, although varied and scientifically sound, are indirect evidence and can only suggest the chemical events that led to the origin of life. There is no direct or primary evidence of what happened because the events left no permanent record that we can recognize. When we consider the development of life, that is the structural and morphological evolution of life, we have direct evidence in the form of fossils preserved in rock.

Precambrian sedimentary rocks younger than 2 billion years contain fossil structures believed to have been laid down by blue-green algae, the most primitive of the plants living today. (See the accompanying geologic timetable for a chronological listing of the periods and organisms important in each period.) The structures are called stromatolites and consist of branched or layered calcium carbon structures. Scientists are reasonably sure that stromatolites are formed by blue-green algae because identical formations are currently being deposited by blue-green algae in shallow tropical seas. Stromatolites have been found in Precambrian rocks from many locations so we can infer that dense mats of blue-green algae were widespread in the early Precambrian seas.

The only known Precambrian animal fossils have been discovered in sandstone beds in the Ediacara Hills of South Australia. These animals, referred to as the Ediacara fauna, represent six different types of organisms, and about 1500 specimens have been collected. The Ediacara fauna consist of two kinds of organisms which are similar to modern jellyfish and soft corals, two kinds which resemble segmented worms, and two kinds which do not resemble any known animal either living or extinct. One of the unknown animals left a circular, fringed impression with three bent arms extending from a central hub; the other left a kite shaped impression with a central ridge. All the Ediacara animals are rather large organisms, one to six inches long; we can easily visualize them in a shallow Precambrian sea creeping over the mud, feeding on dense mats of blue-green algae.

The fossil record, while providing documentation of the form and abundance of past life, also provides us with some challenging puzzles. One of the great enigmas is the relative absence of fossils in sedimentary rocks of the long Precambrian or Proterozoic era. The absence of fossils in the Precambrian is a challenging question because early Cambrian rocks

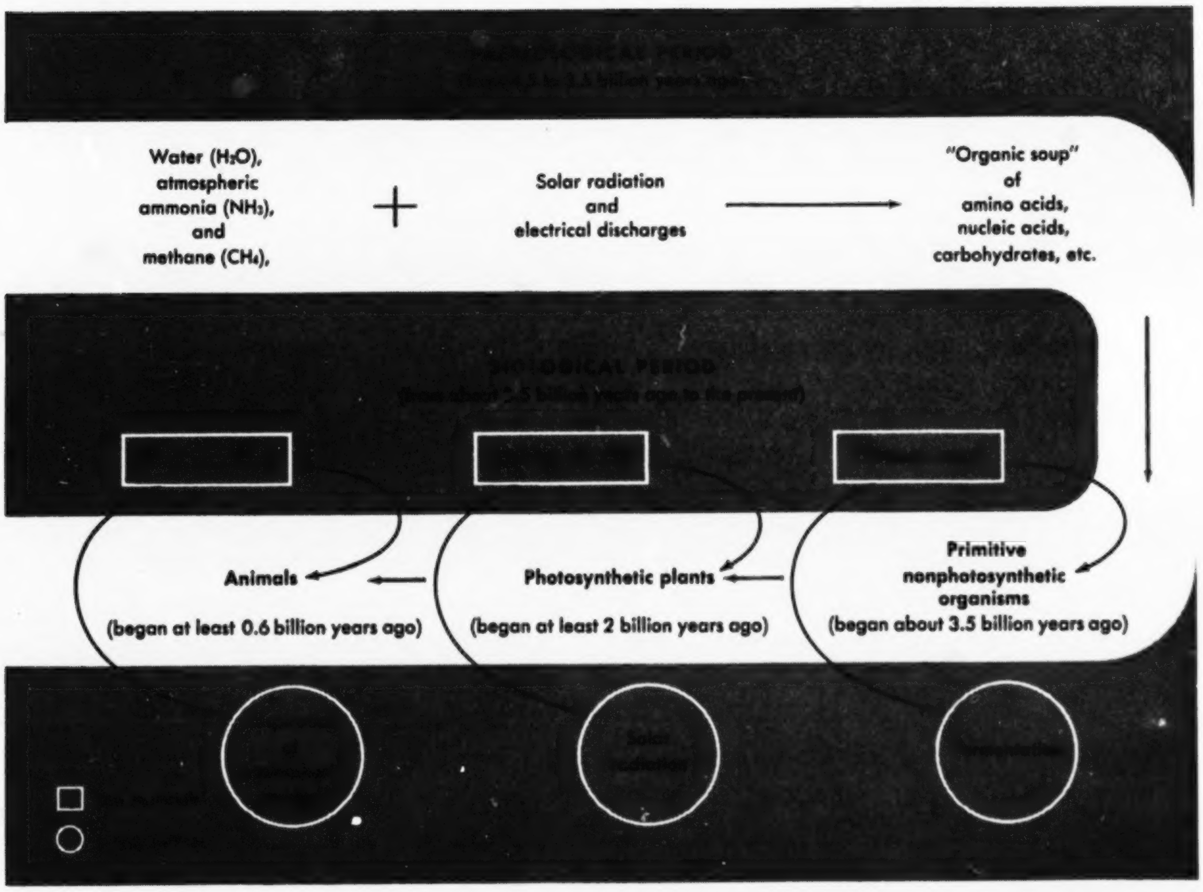
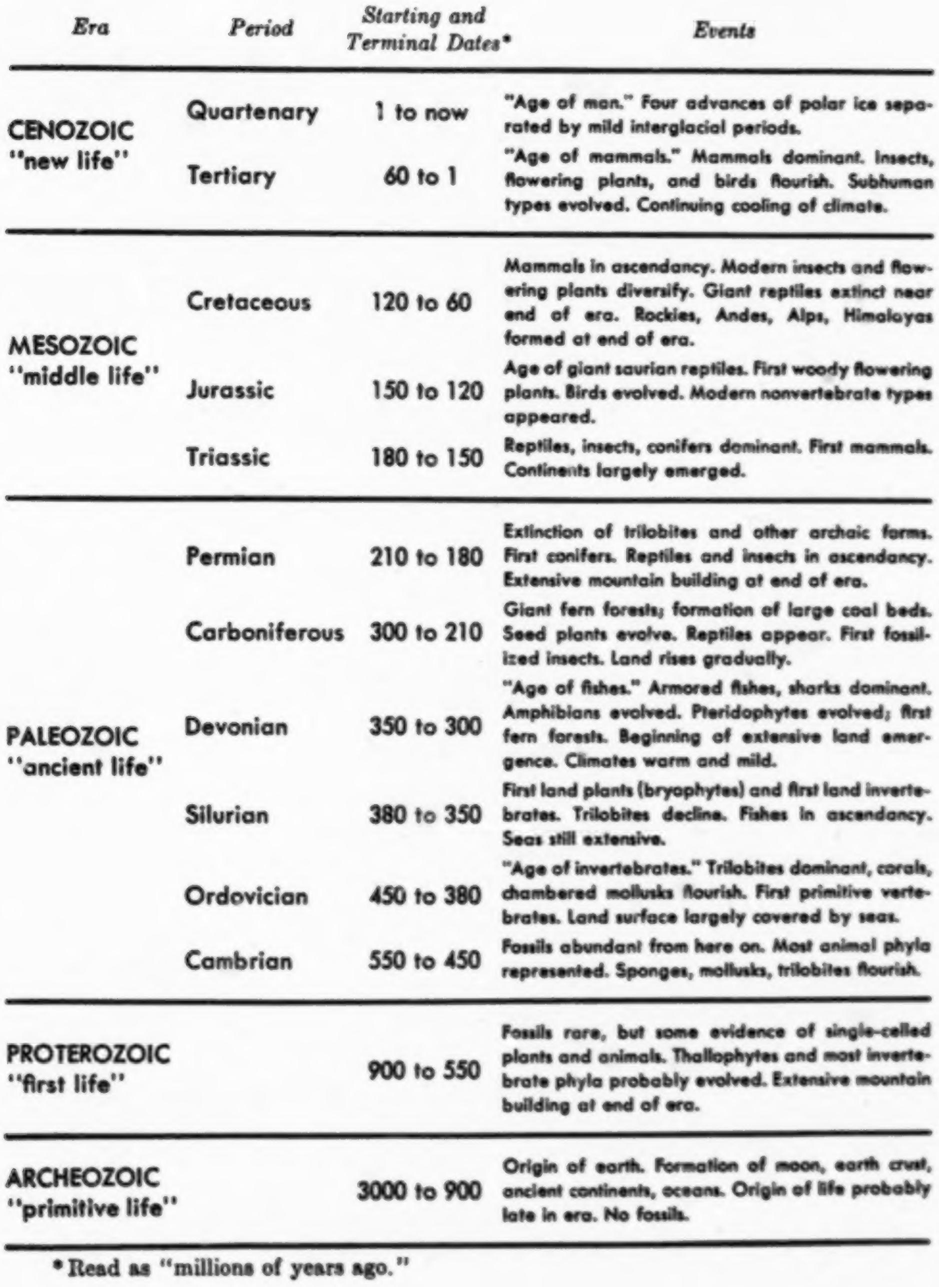

BIOLOGICAL PERIOD
(from about 3.5 billion years ago to the present)
Water (H_2O), atmospheric ammonia (NH_3), and methane (CH_4),
+
Solar radiation and electrical discharges
"Organic soup" of amino acids, nucleic acids, carbohydrates, etc.
Animals
(began at least 0.6 billion years ago)
Photosynthetic plants
(began at least 2 billion years ago)
Primitive nonphotosynthetic organisms
(began about 3.5 billion years ago)

Fig. 2. Stages in the development of life from nonliving matter. (From A. Lee McAlester.)



Era	*Period*	*Starting and Terminal Dates**	*Events*
CENOZOIC ''new life''	Quartenary	1 to now	"Age of man." Four advances of polar ice separated by mild interglacial periods.
	Tertiary	60 to 1	"Age of mammals." Mammals dominant. Insects, flowering plants, and birds flourish. Subhuman types evolved. Continuing cooling of climate.
MESOZOIC ''middle life''	Cretaceous	120 to 60	Mammals in ascendancy. Modern insects and flowering plants diversify. Giant reptiles extinct near end of era. Rockies, Andes, Alps, Himalayas formed at end of era.
	Jurassic	150 to 120	Age of giant saurian reptiles. First woody flowering plants. Birds evolved. Modern nonvertebrate types appeared.
	Triassic	180 to 150	Reptiles, insects, conifers dominant. First mammals. Continents largely emerged.
PALEOZOIC ''ancient life''	Permian	210 to 180	Extinction of trilobites and other archaic forms. First conifers. Reptiles and insects in ascendancy. Extensive mountain building at end of era.
	Carboniferous	300 to 210	Giant fern forests; formation of large coal beds. Seed plants evolve. Reptiles appear. First fossilized insects. Land rises gradually.
	Devonian	350 to 300	"Age of fishes." Armored fishes, sharks dominant. Amphibians evolved. Pteridophytes evolved; first fern forests. Beginning of extensive land emergence. Climates warm and mild.
	Silurian	380 to 350	First land plants (bryophytes) and first land invertebrates. Trilobites decline. Fishes in ascendancy. Seas still extensive.
	Ordovician	450 to 380	"Age of invertebrates." Trilobites dominant, corals, chambered mollusks flourish. First primitive vertebrates. Land surface largely covered by seas.
	Cambrian	550 to 450	Fossils abundant from here on. Most animal phyla represented. Sponges, mollusks, trilobites flourish.
PROTEROZOIC ''first life''		900 to 550	Fossils rare, but some evidence of single-celled plants and animals. Thallophytes and most invertebrate phyla probably evolved. Extensive mountain building at end of era.
ARCHEOZOIC ''primitive life''		3000 to 900	Origin of earth. Formation of moon, earth crust, ancient continents, oceans. Origin of life probably late in era. No fossils.

* Read as ''millions of years ago.''

Table 1. Geological time table (Like earth crust, constructed from bottom upward). (From Paul B. Weisz.)

contain an extremely diversified assortment of highly advanced marine animals. The appearance of such diverse and complex animals would seem to indicate that these groups must have had a long period of development during the Precambrian. This period of development is missing from the fossil record; there is no graded series of oganisms leading up to the complex animals that suddenly appear at the beginning of the Cambrian.

While scientists studying the history of life are accustomed to saying that animal fossils suddenly became abundant at the start of the Cambrian, students should be aware that the statement is actually backward. The Cambrian is a name given to the time in the Earth's history when many fossils were deposited; the fossils provide benchmarks in time for constructing a detailed geologic timetable. The kinds of fossils and the geologic events, such as mountain building, correlate very well and can frequently be dated by radioisotopes; there, we have considerable faith that our geologic time is relatively correct. It is important, however, to remember that the events define time sequence and not vice versa.

To understand the significance of the abrupt appearance of abundant animal fossils it is necessary to be familiar with groups of animals that appeared at that time. Animals are grouped into major subdivisions, each called a phylum (plural: phyla); each phylum is considered to be a basic organizational pattern of life. A phylum should be thought of as a basic, workable life plan on which a number of minor variations can be developed. Some of the phyla you immediately recognize are the vertebrates (fish, birds, mammals -- all minor variations of the basic backbone plan), the arthropods (insects, spiders, crabs), and the worms. Biologistx recognize thirteen major phyla; that means scientists agree that there are thirteen basic life plans existing on Earth right now. Twelve of these thirteen phyla existed during Cambrian times and left a clear record of their existence in rock. The only phylum whose presence was not recorded in the Cambrian rock was our phylum, the vertebrates, or more correctly, the chordates, which appeared 80 million years later during the Ordovician. Of the twelve invertebrate phyla we know today all were present in the Cambrian. No principal phylum has ever become extinct and no major invertebrate phylum has been added since the Cambrian.

It is important to emphasize that while no phylum has become extinct since the Cambrian there has been extensive evolutionary change within the phyla. Subgroups within the phyla die out and are replaced by new groups that represent a new variation on the phylum plan. Extinction has been more and more complete lower in the classification hierarchy; no species has survived from the Cambrain to the present. The idea of phylum persistence and species extinction can be demonstrated with examples from Cambrian fossil beds. Among the marine animals whose remains have been found in a specific Cambrian deposit, the Burgess Shale of British Columbia, are sponges and jellyfish. Any student would immediately recognize the Burgess Shale sponge as being a sponge and the jellyfish as being a jellyfish. This is one way of saying that the student would recognize the phylum; but the student could not recognize the specific kind of sponge or jellyfish because these species have been extinct for millions of years.

The Cambrian sea teemed with marine animals -- the fossil record contains representatives of all the principal groups -- but what of the marine plants? An earlier lecture in this series (see Chapter 10). stressed that living organisms are always part of an interlocking web, or food chain, with photosynthetic plants at the base of the web. What kinds of plants supported the Cambrian food chain? The three dominant photosynthetic plants in marine food chains today are diatoms, coccolithophorids, and dinoflagellates. Each of these groups leaves a distinct fossil record, bu not trace of them has been found as far back as the Cambrian. The startling feature is that no known planktonic plant has been found in Cambrian rocks; in fact, diatoms, coccolithophorids, and dinoflagellates do not appear until the Jurassic period. Other planktonic plants that did not contain readily fossilizable hard parts must have been present in the early oceans, but the nature of these plants is simply not known. Blue-green algae and bacteria (some of which are photosynthetic) have a long Precambrian record and are well represented in Cambrian deposits. It seems most likely that the complex Cambrian ecosystem was based primarily on blue-green algae that grew on the shallow sea floor.

The pattern of marine plant evolution contrasts dramatically with the development of marine animals; the first records of the various plant phyla are spread over an enormous span of time, from the early Precambrian to the Jurassic, with the currently important marine plants appearing last. The marine animals all seemed to appear at once in the Cambrian. Some scientists feel that the sudden appearance of the major invertebrate phyla represents a single evolutionary expansion; that is, thar the phyla developed more or less in one rapid event. It is especially frustrating that there are no intermediate fossils between phyla and no common ancestral groups. Does the uneven and abruptly rich fossil record reflect the true development and abundance of life in the early seas, or is the discontinuity the result of differential fossilization or fossil destruction by geologic processes? These questions are likely to be answered during your life by further probes into Earth and out to our neighbors in the solar system.

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During the Cambrian the land was barren, even sterile; no land animal or land plant existed and none would appear for 200 million years. The seas, however, would not have seemed strange to anyone familiar with marine biology, because the over-all ecology of the shallow waters has not changed from the dawn of life to the present. The specific animals are different, but their way of life is the same. About 60% of all Cambrian fossils are of a group of primitive arthropods called trilobites. These flat animals apparently crawled along the muddy bottom feeding on other invertebrates or blue-green algae; they were segmented and had eyes, head, trunk, and abdomen with numerous undifferentiated jointed legs. Like all arthropods they molted; the numerous molted shells may contribute to the abundance of trilobite fossils. While nothing is known about trilobite ecology, I suspect that their way of life was very similar to that of our common horseshoe crab. Anyone who has seen a horseshoe crab bulldozing along a mud flat at low tide can easily visualize how trilobites lived.

Sharing the Cambrian seas with trilobites were filter feeding clams called brachiopods, sponges, annelid worms, jellyfishes, and a group of mollusks that were the forerunners of modern snails.

The evolutionary events that followed the Cambrian are well summarized in the geologic timetable (Table 1). During the Ordovician, marine invertebrates expanded in numbers and kinds, adding many animals that marine biologists know well. Note that this period is called the "Age of Invertebrates." Among the animals that evolved were corals, snails, clams, sea urchins, and two kinds of predatory animals -- the chambered nautiloids (squids with an external shell) and sea scorpions. Vertebrates first appeared in the late Ordocician in the form of amored, jawless fishes called agnaths. Lacking jaws their mode of life was probably not much different from most of the invertebrates around them. It is believed that they fed by shoveling in soft sediments as they moved slowly along the bottom. The agnaths were small, all less than a foot, and covered with bony plate. They were never very abundant, apparently because the vertebrate body plan did not make a bottom dwelling, sediment eating animal that was a significant improvement over the invertebrates already occupying that niche in the Paleozoic seas. The agnaths, while a small and relatively insignificant group in the ecology of the ancient seas, were very significant in giving rise to jawed fishes called placoderms. The evolution of jaws allowed the placoderm fish to become active predators and to exploit the excellent neural equipment and fast, agile body that is inherent in the vertebrate body plan. The design or engineering features that make the vertebrate superior for an active, predaceous way of life are (1) concentration of the controlling mechanism, i.e., the brain, into one front-end location; (2) location of all the sense organs at the front end near the brain; (3) location of the important catching mechanism, i.e., the jaws and teeth, at the front end and near the brain and sense organs. (To realize what a new life plan vertebrate cephalization [head development] was in the ancient seas, one has only to think of any invertebrate plan with multiple, delocalized nerve ganglia, eyes, or feeding appendages.)

Cephalization is not the only advantage the fish had; the internal, flexible structural support supplied by an internal backbone is mechanically a better system than the articulated exterior skeletons that invertebrates have. The new vertebrate predators were such successful animals that they rapidly expanded in numbers and kinds. In the late Silurian and Devonian seas the placoderms radiated into many ways of life and became the dominant organisms on Earth.

From the Devonian fishes the land vertebrates eventually evolved--first amphibians, then the mighty reptiles, then birds and mammals. The story of the conquest of land by animals and plants is such a long and complex story that we cannot develop it in this lecture.

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The attractiveness of the marine environment for various forms of life is well demonstrated when we examine the re-invasion of the sea by land organisms. It could almost be considered ironic that after a long evolutionary period of land adaptation the reptiles and mammals should produce groups that returned to the oceans. However, the returning groups were new kinds of organisms with new evolutionary potentials, so that their return to the sea is actually just an expansion into the sea by a group possessing a new body architecture that "worked" well on land. While we are not accustomed to thinking of the dinosaurs as being either smart or agile, we can be certain that the giant marine reptiles had better brains and coordination than the fish and sharks that inhabited the Mesozoic seas.

Three distinct groups of large reptiles became fully marine and are well known from numerous fossils. Each group was evolved from a separate reptilian stock, and therefore, represents an independent readaptation to marine life. The plesiosaurs were huge, up to 50 feet, with a long neck and tail, a small head and four flippers. They were really very much like the classic "dinosaur" we all know except that they had flippers instead of legs. Ichthyosaurs were smaller, up to 12 feet, and resembled porpoises and dolphins very much in body shape. From fossil stomach contents we know that these reptiles were active predators, feeding on fish and cephalopods. A third group of marine reptiles were the mosasaurs, a lizard-like form that was also a large, fish eating predator. The mosasaurs evolved and became extinct in a brief span during the Cretaceous. Ichthyosaurs and plesiosaurs first appear in the fossil record during the Triassic and both became extinct in the late Cretaceous. Being air breathers the marine reptiles were not as completely adapted to the marine environment as the fishes or invertebrates, but their superior neural and muscular equipment allowed them to compete successfully with the predatory fish or sharks and to become very abundant in Mesozoic seas.

There is no convincing explanation of why the three groups of marine reptiles all became extinct in the late Cretaceous at approximately the same time as the large land dinosaurs. A changing climate and competition from the emerging land mammals are often considered to be factors related to the mass extinctions of the large land reptiles. These factors would not have greatly affected the marine reptiles, so their extinction is especially puzzling. Another confusing factor is that while the reptile die-off was occurring, no great changes were happening to the fish and shark groups living with the reptiles. There was some extinction and replacement going on, but the main fish families that became established in the Cretaceous have survived to the present.

We should note that each of the surviving groups of reptiles -- snakes, turtles, and lizards -- has representatives that live in the sea, although they are insignificant in numbers and kind when compared to the extinct large marine reptiles. Some of the modern marine reptiles, such as certain seasnakes, are totally marine, living only in the open sea; but the other groups all have to return to land to reproduce.

The mammals were extremely successful on land at the beginning of the Cenozoic era; they radiated in many groups and completely occupied the many niches left vacant by the extinction of the reptiles. The mammalian invasion of the sea was extremely successful and led to the group called cetaceans, which includes the whales, dolphins, and porpoises. As you know these animals are totally marine, living their entire life at sea. Which mammal group they evolved from is not known. Cetacean fossils are known from the beginning of the Cenozoic era, but even the earliest fossils already possess the highly modified structure that is characteristic of cetaceans. What is clear from the fossil record and our modern observations is that the cetaceans have been extremely successful in occupying the niches left vacant by extinct marine repfiles and expanding into new marine niches as the filter feeding baleen whales have done. The cetaceans have evolved into the biggest and fastest growing animals ever to have lived on Earth and also some of the most intelligent animals.

Two other groups of mammals have also invaded the sea, but their adaptation to marine life is considerably less complete than the cetaceans. The very rare manatee is a marine offshoot of the elephant group. While these large herbivores never leave water, they live only in very shallow water, usually in rivers. Man has decimated manatee populations throughout the world and it is doubtful if the group will survive; but if man had not arrived on the scene, the manatees might have become considerably more important elements in the marine system. The most recent and least modified mammals to colonize the sea are the seals, sea lions, and walruses. These animals, derived from the order Carnivora, represent a third and completely independent evolutionary expansion into the marine environment. The seals and their relatives still must return to land to reproduce; therefore, perhaps it is best to consider them as a group still in the process of invading the sea. Some of the evolutionary difficulties of expanding into a way of life that is already occupied by very successful animals is demonstrated by sea lion - killer whale interaction. The sea lions range far to sea when feeding, but their only defense against being eaten by killer whales is to climb out of the water onto rocks. The possibility of evolutionary radiation into a totally marine way of life by sea lions is actually prevented because the bigger and more efficient killer whales have filled that way of life.

Man's modest attempts at marine colonization are not an evolutionary phenomenon, but it is no coincidence that man, like the reptiles and mammals before him, is considering expanding into the sea. The ocean offers man and civilization the same thing that it offered to the reptiles and early mammals: a new and alien environment to expand into and occupy.

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12 Food from the Sea

Aquaculture, its Status and Potential

By

J. H. RYTHER and G. C. MATTHIESSEN

WOODS HOLE OCEANOGRAPHIC INSTITUTION

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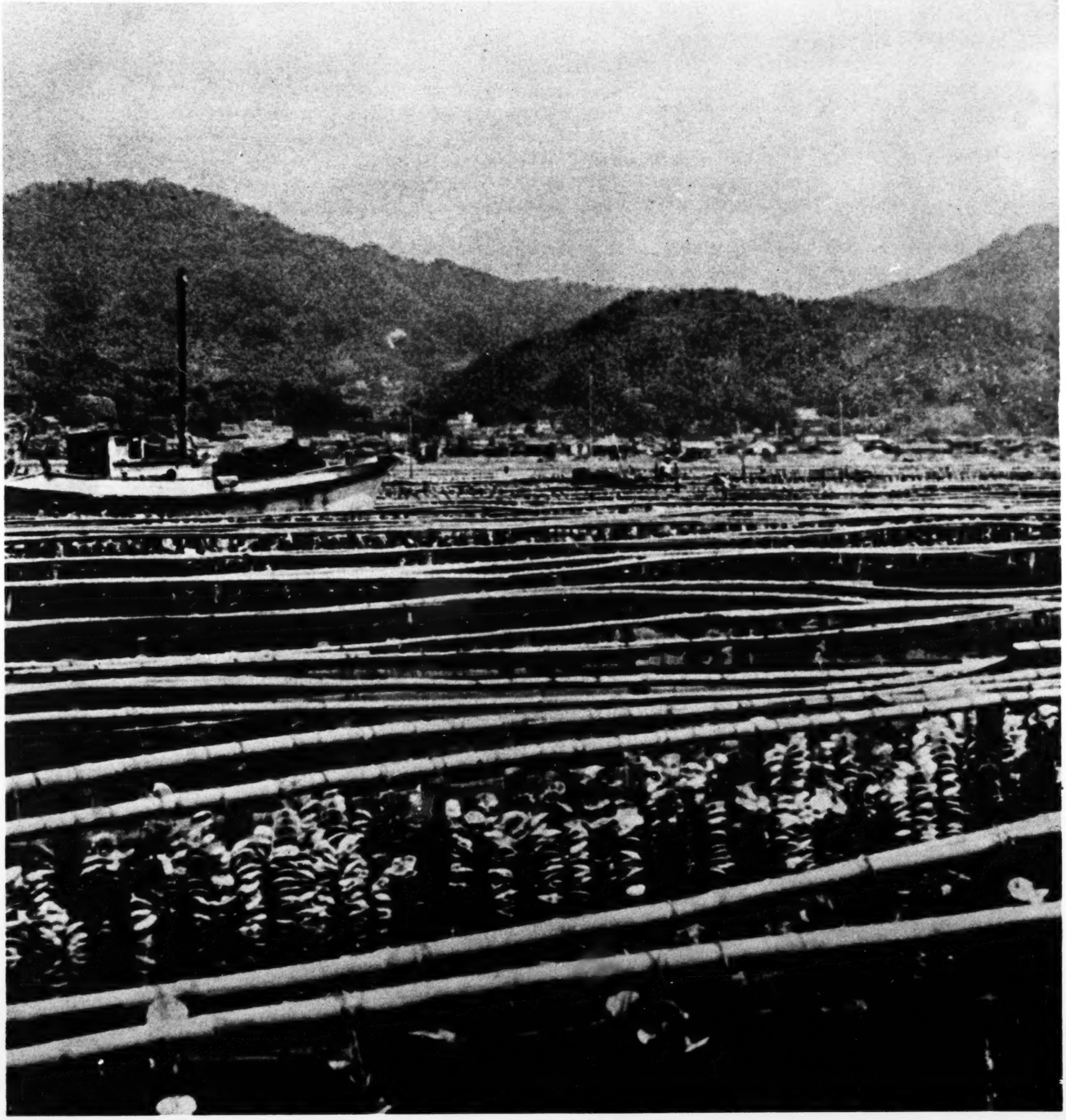


Strings of shells suspended from rafts for the collection of seed oysters shows the Japanese three-dimensional method in Hiroshima Harbor. The strings are pulled up on the tall mast of the ship and deposited on deck.

Aquaculture, its Status and

RYTHER

Potential

by J. H. RYTHER
and G. C. MATTHIESSEN

INCREASING public awareness of the discrepancy between projected world populations and world food supply has caused much speculation regarding the potential food sources of the sea. Some fishery experts feel that future seafood production cannot exceed greatly the current annual level of fifty to sixty million metric tons. Others, on theoretical grounds, envision a possible yield of two billion metric tons or more. Such diversity of opinion shows that it is dificult to estimate the seas' potential food resources with any certainty and weakens the assumption, held by some, that the solution to the world food problem lies in the open ocean.

THERE is more general agreement about the potential productivity of the inshore environment – the coastal waters – largely because their ability to produce significant quantities of protein foods in areas of limited size has been demonstrated clearly in many parts of the world. The yield in terms of kilograms (2.2 pounds) of edible animal protein per hectare (2.5 acres) per year from many bays and estuaries, with no assistance from man, far exceeds average levels of production from the off-shore fishing grounds and is comparable to yields obtained from first rate pasture land. Where man has deliberately intervened and applied certain principles of husbandry to the marine environment, difference in production between agricultural land, the off-shore fishing grounds, and inshore coastal waters is enormous, as the following figures show:

Annual Yield

Area	Product	Pounds/Acre	Kilograms/ Hectare
Pastureland	Cattle	5-250	6-308
Continental Shelf	Groundfish	20-60	25-75
Humboldt Current	Anchovies	300	375
Japan	Oysters	46,000[1]	57,500
Spain	Mussels	240,000[1]	300,000

[1] Not including weight of shell

This table shows clearly that the culturing of shellfish provides an enormous yield, as compared to pastureland and offshore "hunting" methods of fishing.

Such figures are used to illustrate the potential role of aquaculture in alleviating the world's nutritional problem, particularly in the developing countries. To put this subject in proper perspective, we shall discuss the reasons for the extraordinary yields cited above; the various constraints upon the development of aquaculture; and the possible developments that may result in more effective methods of seafood culture.

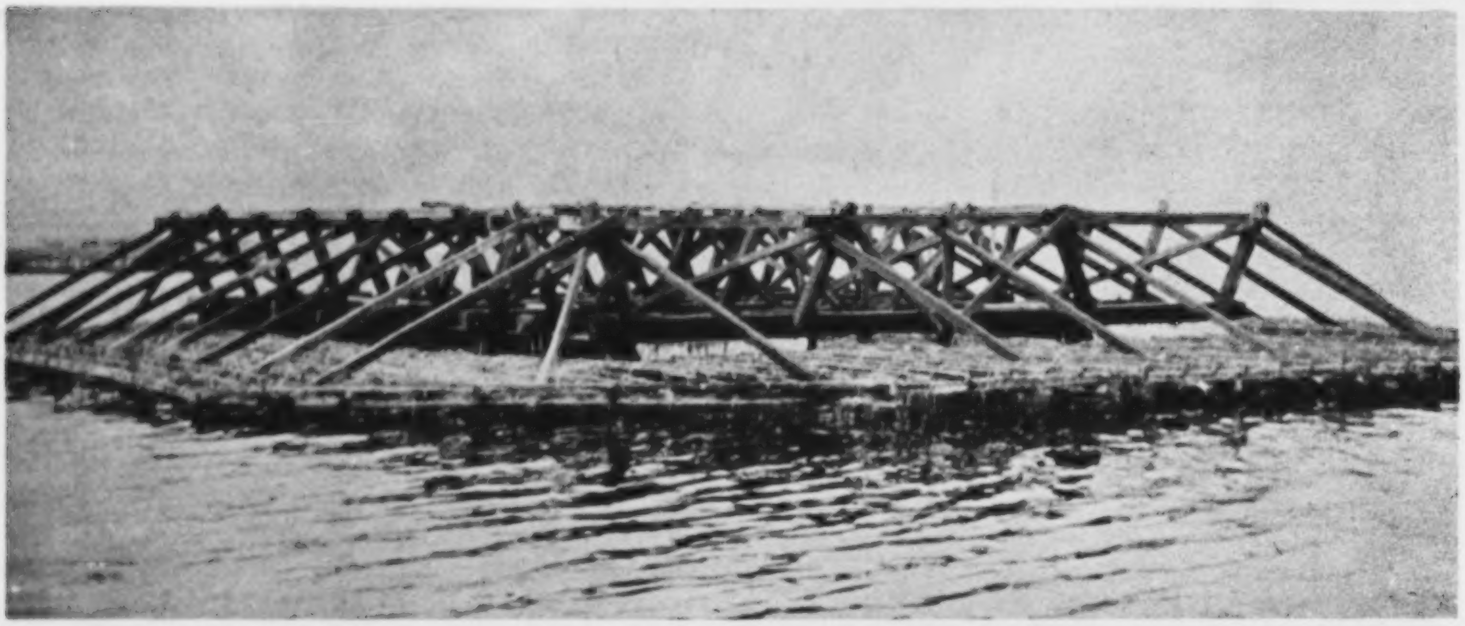
Production in Aquatic Areas

The figures shown for mussel and oyster production apply to relatively small areas, supplied by the action of the tides with large volumes of water. In addition, the shellfish are suspended vertically in the water column, sometimes to a depth of 30 meters, from surface rafts or other devices. Consequently, even though the actual surface area under culture is rather small, the volume of water continually available to the species being cultured is enormous, and the areal yield is deceptively large.

The sedentary, bivalve mollusks such as oysters and mussels expend comparatively little energy to obtain food, which is brought to them by tidal currents. Therefore, a higher percentage of food consumed is converted into flesh than might be the case for animals that must actively pursue their food. Also, no energy need be expended to maintain a constant body temperature, an advantage not enjoyed by terrestrial livestock. Fish have a further advantage over livestock since, due to the buoyant effect of water, they do not require heavy skeletal structures. Therefore, a higher percentage of total weight is in flesh rather than in bone.

The amount of particulate matter — in the form of micro-organisms and detritus — is far greater in the inshore environment than in the open ocean. This material constitutes an important source of food for many species that are being cultured. In fact, the great majority of aquatic animals selected for intensive culture are herbivorous during part or all of their life cycle. Therefore, if a food conversion efficiency of 10 per cent is assumed, 100 kilograms of microscopic plants (phytoplankton) might produce 10 kilograms of mussels — the herbivore — but only one kilogram of cod — the primary carnivore — and perhaps only one-tenth of a kilogram of swordfish, the secondary carnivore.

Aquaculture by definition implies a certain degree of control over, or manipulation of, the organisms and/or its environment. The cultured species is not fugitive and hunted at random, but is in fact thoroughly and efficiently harvested. Usually certain techniques are employed to improve chances of survival of the young, reduce natural predation, avoid disease, in short, to increase the likelihood of survival from fertilized egg to maturity.



A modern mussel culture raft near Vigo, Spain. One thousand ropes, each ten meters long, are suspended from the raft. Annual production is 60 tons of mussel meat.

These are perhaps the major reasons why levels of food production by aquaculture are impressive. Figures as those shown on page 4, inevitably are applied to much larger areas, with dramatic—albeit unrealistic—results. It has been calculated, for example, that the total annual seafood production of the United States could be doubled, if one-third the total of Puget Sound was devoted to oyster culture by Japanese, e.g., three-dimensional, methods. Such extrapolations are sufficiently valid on a theoretical basis to arouse the curiosity, if not excitement, of those concerned with world food needs. But such estimates cannot be accepted as realistic because there are various constraints upon aquaculture.

Constraints upon Aquaculture

Food production by aquaculture requires both technical proficiency and incentive. Japan, combining technical skills with an awareness that a great percentage of her protein foods must come from the sea, has made unquestionably the most significant advances in this field. The sociological and legal climate is, of necessity, favorable, and Japan regards food production as the primary function of her coastal waters.

The United States, despite her technical competence, has not placed much emphasis upon aquaculture, largely due to lack of incentive. With abundant sources of protein foods available from the land, and with lethargic public demand for seafoods other than luxury items, such as oysters, shrimp, lobsters, etc., interest in aquaculture from either the nutritional or economic standpoints is limited. Quite recently, and because of increasing public demand for luxury seafoods, certain private interests have started aquacultural enterprises with anticipation of eventual profit. Others have done so because traditional methods of production have failed and certain culture practices have become necessary. By and large, however, the incentive to farm, rather than hunt, seafood has been lacking.

Lack of economic incentive is not the only reason why aquaculture has been slow in developing. Fishery resources have long been regarded as common property, and the coastal waters as public domain. Private efforts to assert exclusive rights to coastal waters for aquacultural purposes are frequently thwarted by local statutes reinforced by public resentment. (It might be noted that conflict between public rights and private interests with regard to seafood culture is no less real in Ireland or the Hawaiian Islands, for example, than it is in New England). Ironically, where private ownership and responsibility is practiced—as on certain oyster beds in the Chesapeake Bay—the yield is incomparably greater than that derived from public grounds, for obvious reasons.

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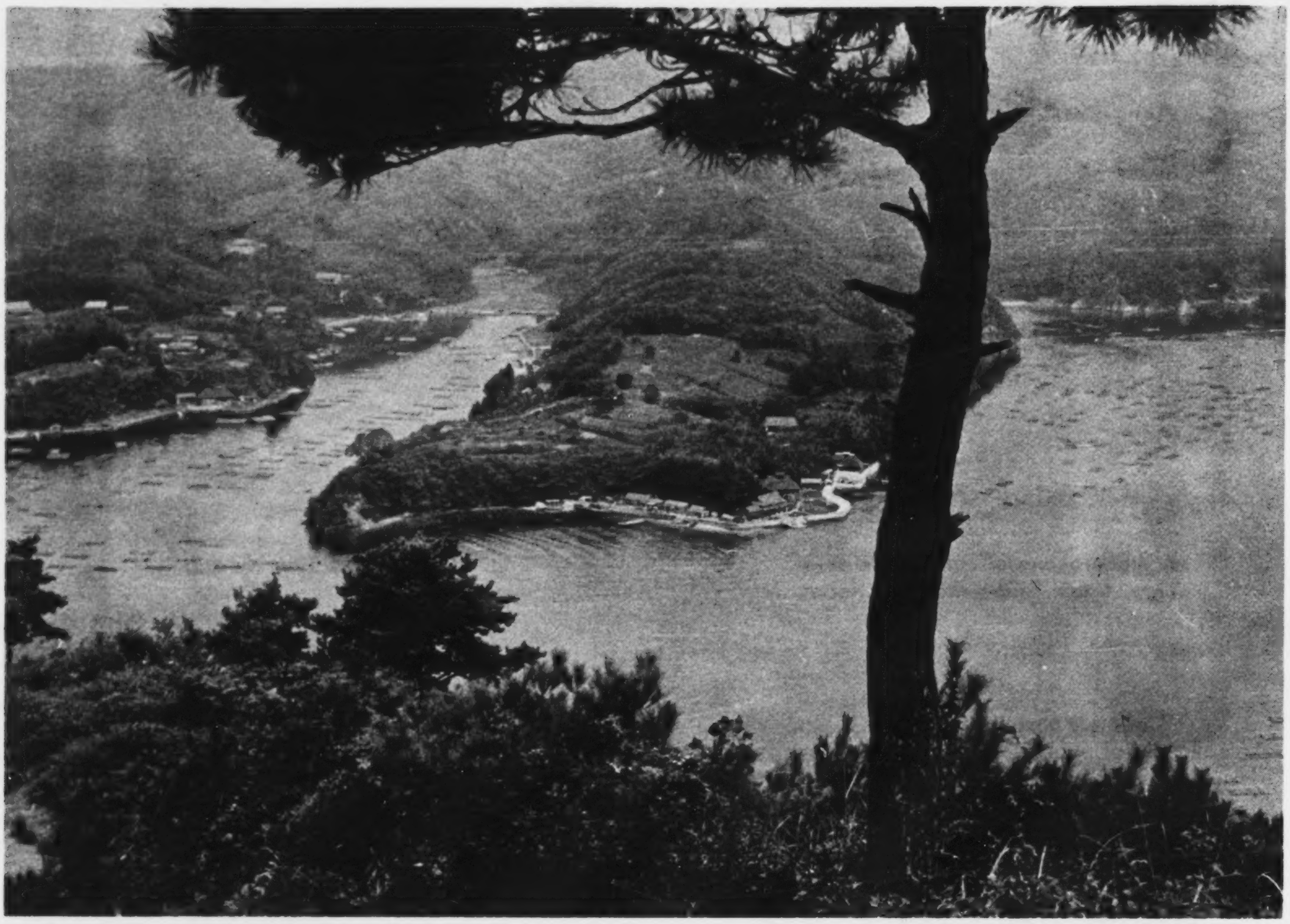


RYTHER

In Kessenuma Harbor, Japan, more than 5,000 oyster rafts cover some thirty square kilometers. It is obvious that such use of U.S. coastal waters would be objectionable to watersports' interests.

Projects involving use of coastal areas for aquaculture, if not prevented by statute, may be frustrated by competitive interests. At best, such interests may involve recreational activities—boating, water skiing, etc.—that exert ever-increasing demand upon water space. At worst, they involve the transforming of bays and estuaries into convenient receptacles for industrial and domestic wastes. The potential value of such areas for food production is subsidiary to other, more immediate, economic considerations.

Such constraints are economic, social or legal in nature. In areas of the world where the need for protein foods is critical, the equipment necessary to implement aquaculture—capital and trained personnel—may be the limiting factor. In these situations, culture is limited to species that produce the maximum amount of food with minimum expense and sophistication of method. Through technical assistance, it should be possible to reach much higher levels of production, not only for species that are being cultured now, but possibly for exotic species as well. However, certain of the technical problems are formidable.

Problems in Culturing

In the case of bivalve mollusks of commercial importance, much has been learned about methods of culture. These animals are attractive for intensive culture since they are herbivorous, sedentary, highly prolific, of considerable nutritional value, and frequently command a high market price. Largely as a counter-measure to failure in natural reproduction, oyster and clam "hatcheries" have in fact been established in Europe, Japan, and the United States for purposes of producing large quantities of seed shellfish. In oyster hatcheries, adults are sexually matured by appropriate temperature manipulation, and then induced to spawn by chemical or thermal excitation. The larvae are reared on a diet of cultured phytoplankton, in tanks in which the water is pre-warmed, pre-filtered and changed daily. After the larvae metamorphose, the tiny juveniles, now attached to shell, are conditioned to the natural environment by exposure to appropriate water temperatures and eventually transferred to the oyster beds, where, it is hoped, they will mature to marketable size. Some of the hatcheries in New England may produce several hundred million juvenile oysters each year.

Commercial hatcheries have not been in operation long enough to allow a realistic evaluation of their economic merits. The available evidence indicates a high mortality rate among the juveniles on the natural beds. In Long Island Sound, off New York, where most of the hatchery produced oysters are set out, the loss is primarily due to natural predation—by starfish and oyster drills—and smothering of the oysters by siltation. The important point is that once the oysters are exposed to the natural environment, the oyster culturist has lost a large degree of control.

The loss from bottom-crawling predators and siltation might well be avoided by adopting Japanese methods. Raft culture has not been considered practical in Long Island Sound, because of boat traffic and pollution in the sheltered coves, and because of adverse weather conditions in exposed areas. Labor costs for assembling oyster strings and constructing and maintaining rafts must also be considered. (In Japan, the value of the eventual harvest outweighs the comparatively low labor costs).

A superficially attractive alternative would be to culture oysters in ponds or excavated pools protected from the sea, in which a maximum amount of biological control might be applied. Unfortunately, to grow well an oyster needs either huge volumes of water, continuously replaced to keep up the supply of natural planktonic food, or else large amounts of algae must be cultured as supplementary food. So far, neither alternative is economically justified.

In the case, then, of oysters and other shellfish, the problem is not one of providing enough off-spring, but rather that of rearing the juveniles to marketable size with minimum loss and at reasonable cost. Precisely the opposite problem exists in the case of the milkfish, a species cultured in brackish-water ponds in many parts of Southeast Asia. In certain areas, over one thousand kilograms of milkfish may be harvested from a single hectare of pond each year, and large tracts of mangrove swamp have been developed for this purpose.

Milkfish

The milkfish spawns at sea, and the fry are gathered by nets when they move inshore. They are stocked in shallow ponds, to which fertilizer may have been added to stimulate growth of algae, bacteria and various protozoa. The milkfish thrives in these enclosed areas, feeds readily upon the algal mats—known as "lab-lab"—and may exceed 0.5 kg. in weight in less than one year. Because it is herbivorous, a rapid grower, fleshy, and tolerant of the crowded conditions in shallow, stagnant ponds, it is in many respects an ideal species for intensive culture.

The major limitation upon milkfish culture is that it is difficult to catch fry consistently, due to unpredictable fluctuations in abundance. To date, efforts to stimulate reproduction in captivity have failed. It might be noted that certain species of mullet—also a brackish-water fish that normally spawns at sea—have been induced to spawn by injecting the adult with pituitary hormones. This technique might be applied successfully to milkfish, but it should be remembered also that as is true of mullet, it may be difficult to supply appropriate food for the larval fish.

A somewhat different problem occurs in the rearing of plaice and sole in hatcheries on the Isle of Man. Adults of these species are held in special spawning tanks, and the fertilized eggs are readily obtained. The resulting larvae are reared through metamorphosis, eventually settle to the bottom, and may mature to market size in densely stocked pools. It has been estimated that the entire annual catch in Great Britain could be cultured in shallow ponds covering an area of only one and a quarter square miles.

Unfortunately, these fish are carnivorous. Before the larvae metamorphose and settle to the bottom, they consume large quantities of small crustaceans which, for hatchery purposes, must be carefully cultured. To be economically profitable, a hatchery must produce fish in large volume, which in turn implies an abundant, readily available supply of food. If the cost of food, plus the expenses involved in maintaining a clean and healthy environment in the rearing tanks, approaches the eventual market value of the fish—as it does in this case—then the economic justification of the operation is questionable. It might be proposed that attempts to culture carnivorous species are unrealistic, and that emphasis should be placed upon herbivorous species. However, the herbivorous mollusks appear to be so selective as to the type of algae they will assimilate that providing large volumes of suitable food involves a considerable investment.

Lobsters

Because of its high market value, and because it feeds readily in captivity upon fish scraps, shellfish and other types of food that need not be cultured, the lobster has excited the interest of prospective seafarmers. Adult lobsters have been successfully mated at the Massachusetts State Lobster Hatchery on Martha's Vineyard, and the resulting larvae reared through metamorphosis. Juvenile lobsters have been reared to marketable size in this hatchery.

However, even if it were economically feasible to feed large quantities of lobsters on such foods, the culturist would be faced with a possibly more serious problem: cannibalism. Lobster are particularly vulnerable to other lobsters immediately after molting before their shell has hardened. Therefore, they should be held in isolation as much as possible. In view of the extensive period of time required for a newly-hatched lobster to attain marketable size—under normal New England water temperature conditions, this is estimated to be five years —the idea of feeding and maintaining large numbers of lobsters in separate compartments, in a manner somewhat similar to modern poultry farming, appears somewhat impractical at present.

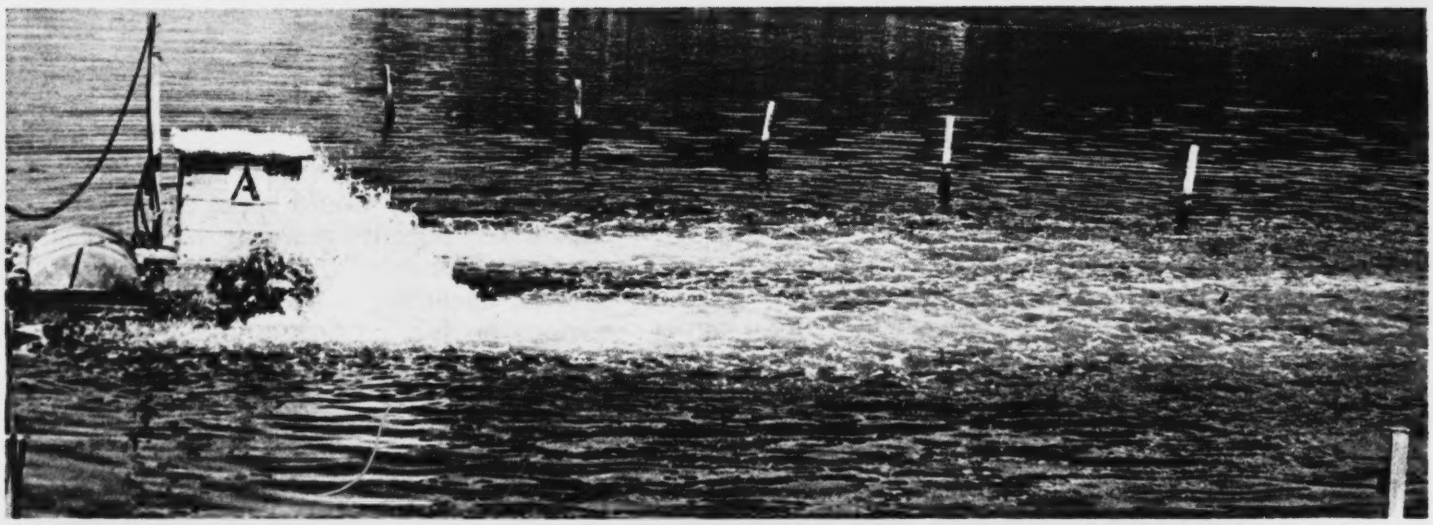
The problem of cannibalism also occurs in the culture of certain species of shrimp and prawns. However, the major difficulty, and one that appears so frequently in various aquacultural endeavors, is that of providing sufficient amounts of suitable food at realistic cost. In Japan, where shrimp culture is most advanced, larval shrimp are obtained from egg-bearing females captured in the sea. These larvae initially are fed cultured algae and, at subsequent stages of development, small crustaceans (which also must be cultured). After a period of twelve days or so, the larvae metamorphose into the adult form, and a diet of fish scraps or ground clams is provided.

The cost of rearing shrimp in such fashion—not to mention the expense of maintaining the culture pools free of parasites and disease—would seem prohibitive. It is profitable in Japan because labor costs are relatively low and because there is such a high demand for shrimp, that the price is high, even by U.S. standards.

An interesting variation on the problems of shrimp culture involves the giant prawn, common in brackish and fresh water ponds throughout Southeast Asia. One particular species may exceed 0.15 kg. in weight, and the market value makes it desirable for culture. Investigators in Hawaii have cultured this species through its larval and post-larval stages, despite its complex feeding habits, and have released the juveniles in ponds from which it was intended they would eventually be harvested. At this point, however, the elusive prawn has refused to cooperate and has successfully defied all efforts — by trap, seine, or other device—to effect its capture.

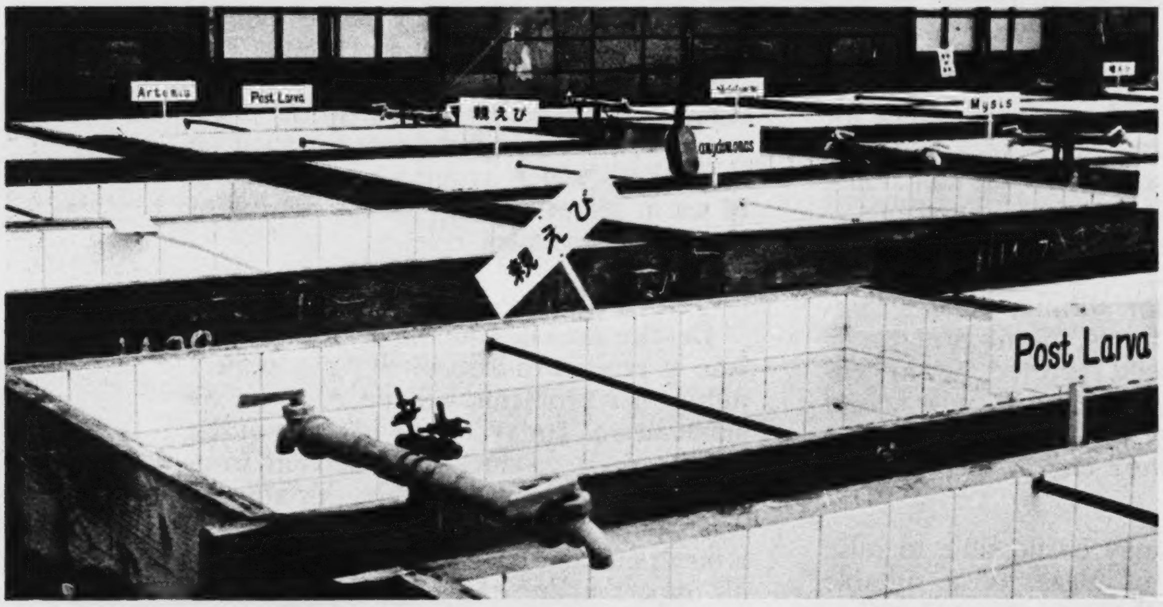
Synthetic Food

With few exceptions, the major technical problems associated with aquaculture appear to be resolvable if sufficient time, scientific talent and capital are invested. Although it is a highly diversified enterprise with respect to the species cultured, geographic location, methodology, and even motivation, the major problems—reproduction and nutrition—appear to be common throughout. At this point, it would seem likely that development of an appropriate, possibly synthesized, food for shrimp might have immediate and beneficial application to, for example, plaice culture on the Isle of Man, or lobster culture in Massachusetts.



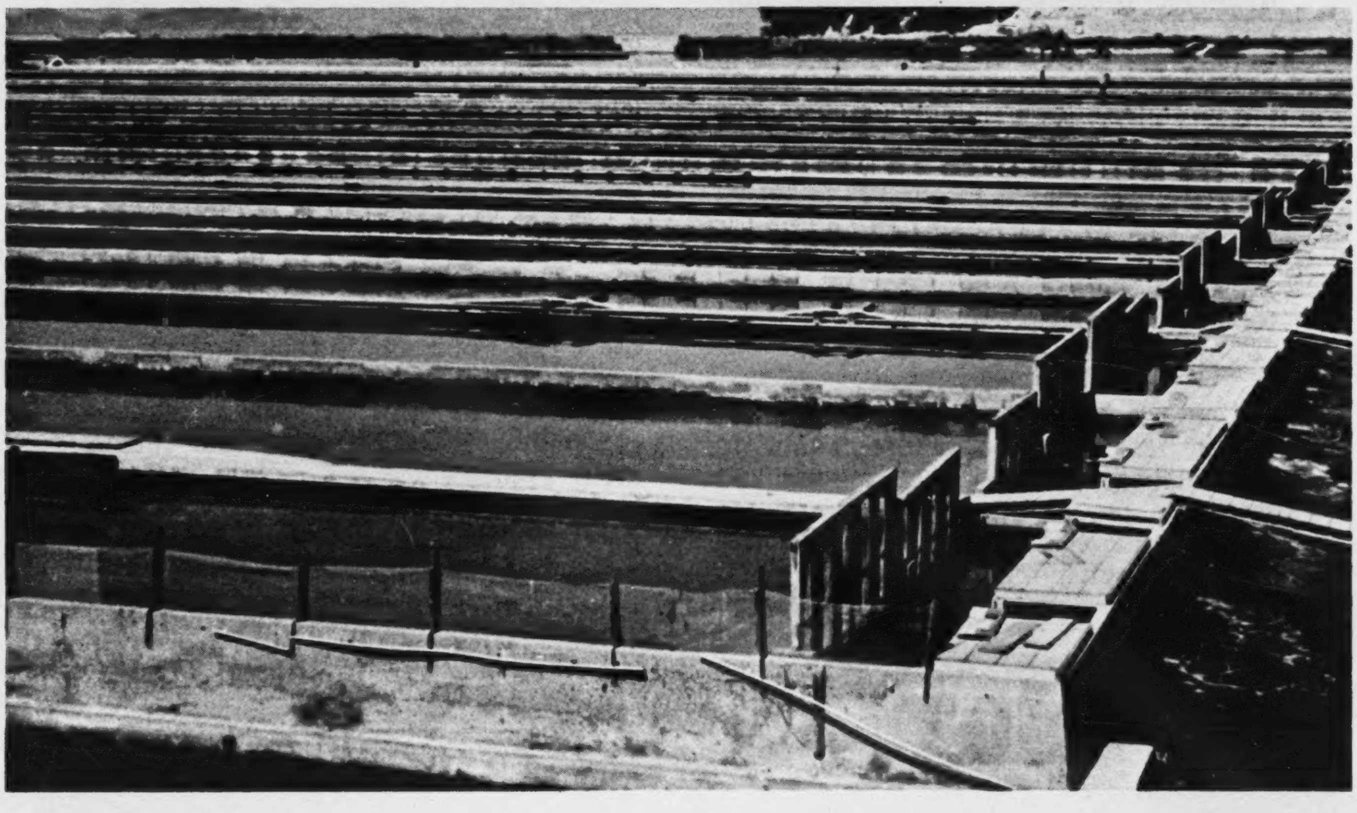
An artificial pond used for shrimp culture in Japan is aerated by an electrically driven paddle wheel.

The heavy feeding of the shrimp and the high organic content of the water makes aeration necessary.



Six million juvenile shrimp can be raised each month in these heated ceramic tanks at Takamatsu, Japan.

Shrimps are raised to adult size in these oudoor tanks at Takamatsu. The tanks are 100 x 10 meters. Some 80,000 liters of water per hour is pumpea through the tanks.



The Future of Aquaculture

The ultimate usefulness of aquaculture will depend to a large extent upon our ability to reduce cost of production, an achievement so clearly demonstrated by the poultry industry. Modern poultry production has been the result of the combined efforts of nutritionists, geneticists, pathologists, engineers, and representatives of other scientific disciplines, and the development of aquaculture as an efficient method of producing food will require an equivalent combination of talents.

Perhaps the most significant accomplishment would be the development of artificial, as opposed to natural, foods for various species. Just as chickens, and even trout and catfish, are fed pellets containing the necessary biochemical ingredients—amino acids, minerals, vitamins, etc.—it should be possible eventually to synthesize nutritious diets for shrimp, bivalve mollusks and other forms. Some progress in this regard has been reported, but in general the marine aquaculturist must accept the fact that, in order to raise one species, he must also culture one or several more species as food.

Eventually it may be possible to raise large quantities of algae, of a suitable variety, at costs that are not prohibitive. Certain green algae, such as *Chlorella* and *Scenedesmus,* are being cultured in sewage treatment processes in considerable volume—40,000 to 60,000 kg. of algae (dry weight) per hectare of pond surface area per year—and with a high protein and vitamin yield. The dried algae has been incorporated in livestock food with beneficial results. Similar techniques might be employed to culture forms more useful for aquaculture, and simultaneously, help relieve the increasing problem of sewage treatment and disposal.

Genetics

Genetics already has played a prominent role in fresh water fish culture, notably in the hatchery production of salmon and trout. In the Pacific Northwest, salmon and trout parent stock are bred selectively to produce offspring with superior qualities, e.g., rate of growth, hardiness, fecundity, etc. There would seem to be little reason why selective breeding might not be applied profitably to a wide variety of species, including lobsters, oysters, and various fin fish.

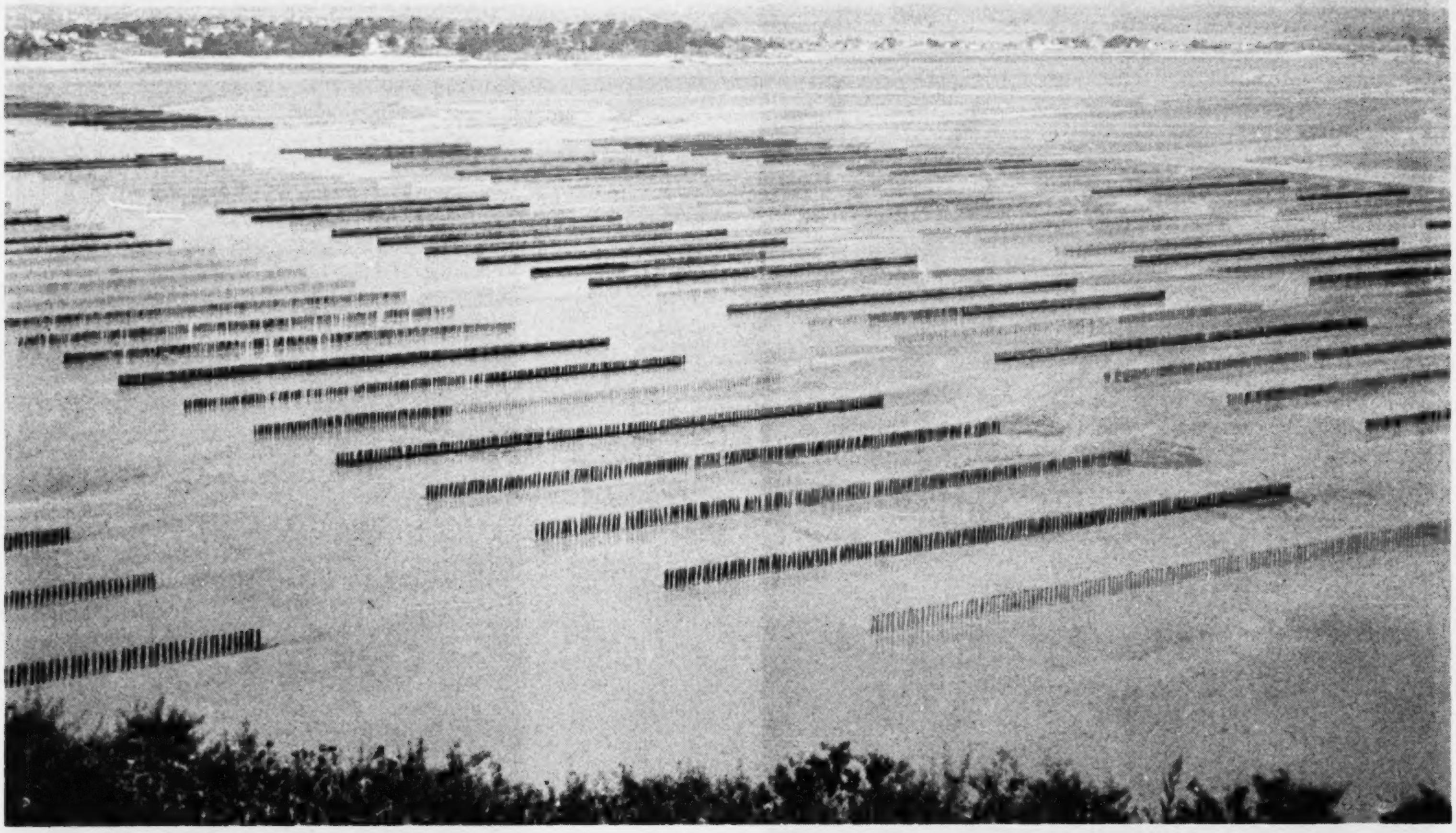
The rapid development of electric generating plants along the coastlines may also be of benefit to aquaculture, at least in temperature latitudes and if properly managed. For many species occurring in temperate waters, growth is possible only during the warmer months of the year. It might, therefore, be economically advantageous to establish culture operations in the vicinity of generating plants, where seawater used for cooling condensers is continually discharged at higher temperatures. Use of cooling water would seem to be particularly appropriate for shellfish hatcheries, which require large volumes of warm seawater daily for the rearing of larvae and juveniles.

Hunger Problem

Despite such developments, it is unrealistic at present to assume that the world's nutritional problems will be resolved by aquaculture. Today, only 3 per cent of the world's food production is derived from the sea. If, as seems unlikely, this amount was doubled during the next decade as a result of intensive aquaculture, the overall impact upon total food supply would not be impressive. Already more than 60 per cent of the people in underdeveloped areas, which comprise two-thirds of the world's population, suffer from undernutrition, malnutrition, or both; yet, as certain social scientists point out, the technical competence for fully exploiting aquatic food resources in these areas cannot be developed fast enough to avoid famine.

On the other hand, famine might at least be alleviated through aquaculture, even by applying techniques currently in use. The Food and Agricultural Organization of the United Nations has estimated that there are now 37 million hectares (92 million acres) of swamp and aquatic areas available for fish culture in South and East Asia. If this entire area was developed for the culture of milkfish at

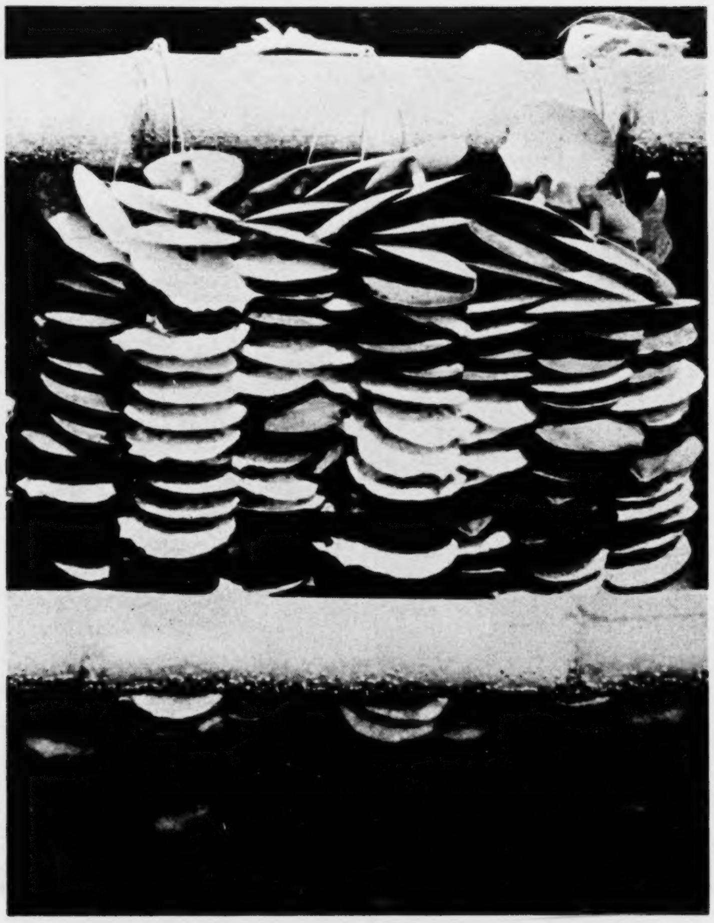
(continued on page 14)



Mussel culture on poles (bouchots) near St. Malo, Britanny. The method was discovered accidently in A.D. 1235 by a shipwrecked Irishman, Walton, who tried to snare seabirds on crude nets set between poles on the mud flats. Young mussels settled on the woven nets.

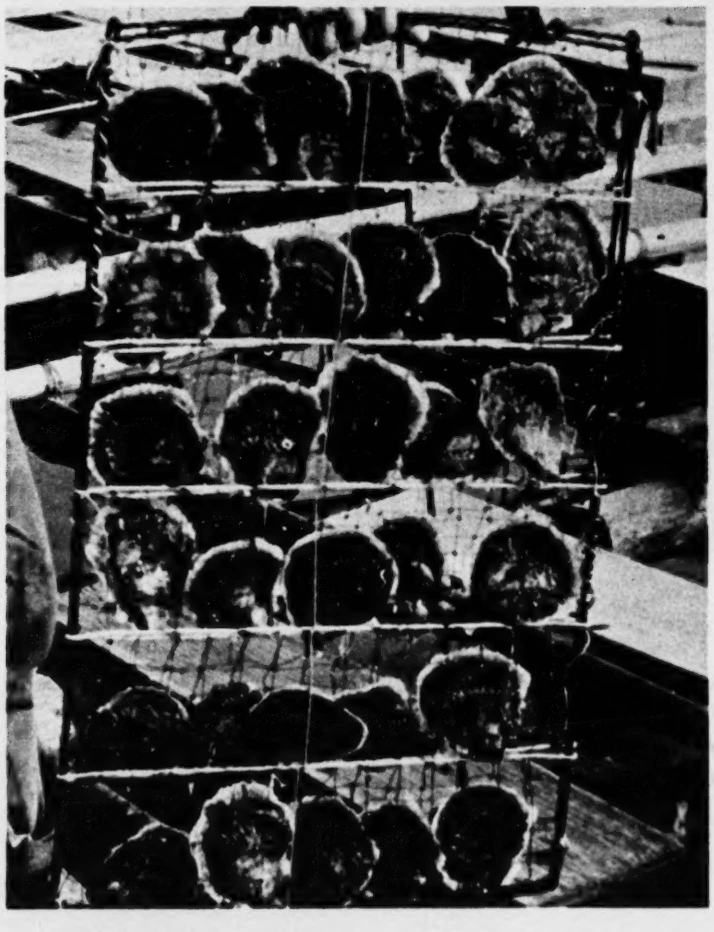
Today, ropes on which young mussels have set, are wound spirally around the poles. ▶

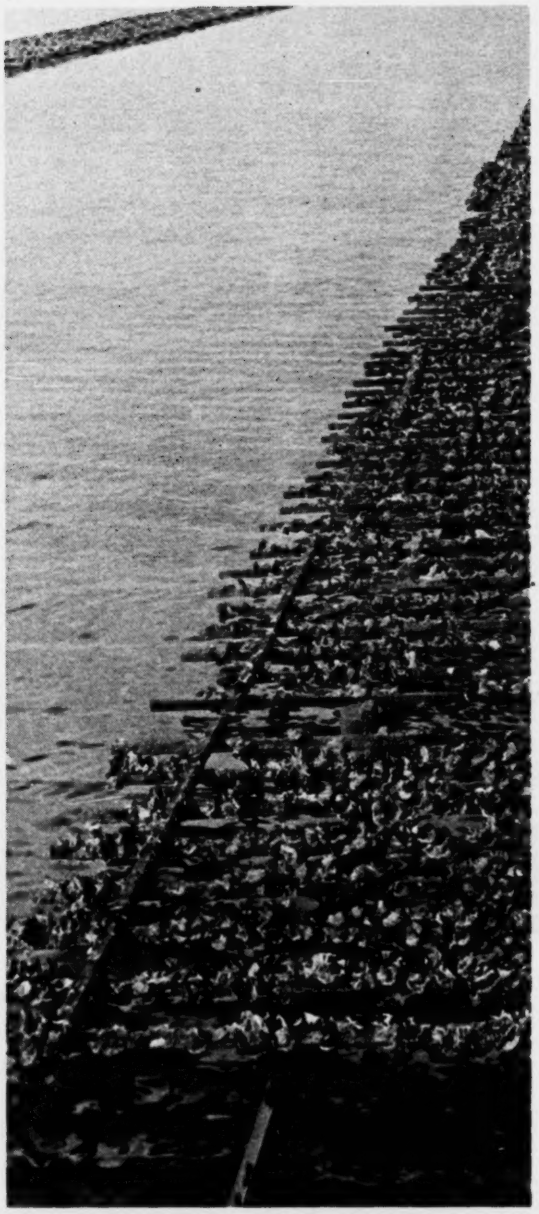
Adult mussels ready for harvesting on the poles of Britanny. The extreme ranges in tide in the area ease the harvesting problem.



A string of scallop shells separated by bamboo spreaders for the collection of seed oysters at Hiroshima Bay.

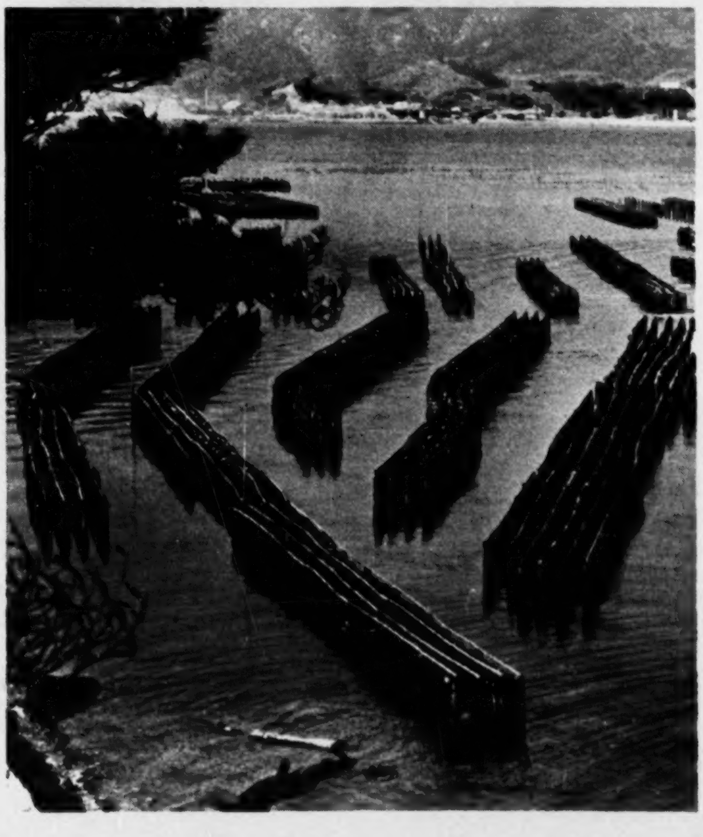
Arranged neatly in a rack these European flat oyster are grown suspended from bamboo rafts in Kessenuma Bay.





Low tide in Georges River, New South attached to tarred wooden sticks.

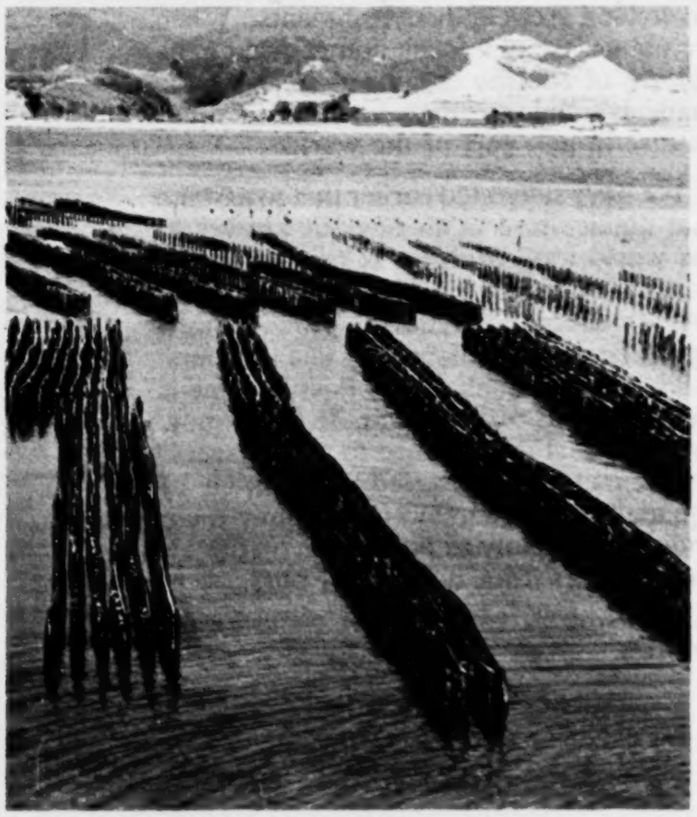
A red algae (Porphyra) culture in the Inland Sea of J



WOLF

Wales, Australia, shows young oysters

apan. Japanese consider Porphyra cakes a delicacy.



An impressive pile of shells represents one month of oyster shucking at a Hiroshima Bay establishment with thirty rafts.

Abalone also are cultured in the Japanese raft system. They are suspended from the poles in plastic containers.

levels of intensity approximating those achieved routinely in Taiwan, i.e., 1000 - 1500 kilograms of fish produced per hectare per year, the resulting yield would exceed 30 million metric tons of high quality protein food per year, or more than half the total world production of seafood. Clearly such a contribution would not erase world hunger, but it could avert famine for many in a part of the world where, as is also true of Africa and Latin America, malnutrition is chronic.

Aquaculture should also be considered from the point of view of efficient resource use and future resource management. It has been estimated, for example, that algae may be cultured, on sewage, so intensively as to yield 20,000 kg. (10 tons, dry weight) of digestibe protein per hectare of pond per year, or roughly ten to fifteen times as much protein as a hectare of land planted with soybeans, and 25 to 50 times as much as one planted with corn. Similarly, while an average hectare of pastureland produces 150 kg. of beef (on the hoof) each year, production of trout, reared in flowing water, has exceed 1.5 million kg. per hectare per year. Clearly aquaculture, as a means of producing food, makes comparatively small demands upon space.

Possibly more relevant with respect to resource use are the comparative demands upon fresh water by terrestrial agriculture and aquaculture. Soybeans and wheat reportedly yield only 230 and 46 kg. (500 and 100 lbs.) of protein respectively, for every acre-foot of fresh water consumed, whereas, 2,300 kg. of algal protein are produced per acre-foot. It has been estimated that one kg. of beef has required 66,000 to 132,000 kg. of water in its production, if the amount of water necessary for producing the food consumed and the amount taken directly by the animal are included. This is in striking contrast with seafood production, which is essentially non-competitive for our fresh water resources.

Within the next twenty years, the world's population may double. This implies that, in order to maintain present living conditions and yet satisfy demands for habitation, industry, recreation, agriculture, and refuse disposal, twice the amount of space and fresh water will soon be required. Aquaculture will not resolve this problem any more than it will resolve the problem of human nutrition, but it suggests an approach to resource use that is efficient, beneficial, and possibly necessary.

New Program

AT Woods Hole we are developing a program in aquaculture with a dual approach: to study the basic environmental requirements of some marine animals of existing or potential importance to mankind, and to apply the obtained results of the basic biological principles involved to the intensive and controlled culture of such animals. In a sense, such a program will merely be an extension of current research on the biology of marine organisms. Still, it represents a departure from purely basic research in that emphasis will be placed upon species of economic importance, and upon culture techniques which may lead to economically viable, and socially desirable methods of producing food.

This program will include basic biological research related directly to aquaculture; investigations of the possible application of environmental modifications to aquaculture, such as domestic pollution, thermal pollution, etc. and technical and economic studies on the production of commercially desirable species on a pilot scale. The ultimate objective is to establish basic principles of aquaculture that may be applied to a wide range of species in diversified areas and environments. When we obtain useful information regarding the culture of specific organisms, this will be made available to others involved in aquaculture in any part of the world.

We have suggested earlier that to assume that aquaculture is an obvious answer to the world food problem is unrealistic. A noted U.S. expert on fisheries has stated: "As a panacea for relieving protein shortage in latitudes and societies such as ours, mariculture is nonsense!" Possibly this is true. On the other hand, there is now sufficient factual evidence to encourage, if not demand, a concerted exploration of aquaculture's potential and to apply these findings as rapidly as possible in "latitudes and societies" not necessarily ours.

ALL PHOTOS IN THIS ARTICLE WERE BY DR. RYTHER, UNLESS OTHERWISE NOTED.

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Applied Oceanography: Aquiculture - Oyster and Mussel Fisheries
The Sea-Fisheries
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Ingle, Robert M., and William K. Whitfield, Jr., 1968. Oyster Culture in Florida. St. Petersburg: Florida (State) Board of Conservation Marine Laboratory. 25 pp. (Educational Series No. 5.)

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Also available from: National Fisherman, 22 Main Street, Camdem, Maine 04843.

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Articles:

Ayers, Robert U., 1967. Food. Science Journal, Vol. 3, No. 10, 100-106.

Bowers, A. B., 1966. Farming marine fish. Science Journal, Vol. 2, No. 6, 46-51.

Emery, K. O., and C. O'D. Iselin, 1967. Human food from the ocean. Science, Vol. 157, No. 3794, 1279-1281.

Gulland, J. A., 1968. The ocean reservoir. Science Journal, Vol. 4, No. 5, 81-86.

Holt, S. J., 1969. The food resources of the ocean. Scientific American, Vol. 221, No. 3, 178-194.

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Rythor, John H., 1959. Potential productivity of the sea. Science, Vol. 130, No. 3376, 602-608.

Shellbourne, J. E., 1964. The artificial propagation of marine fish. In: F. S. Russell, editor. Advances in Marine Biology, Vol. 2. London: Academic Press, pp. 1-83.

Sea Frontiers, Oceanology International, Undersea Technology, and the various fishery trade journals also occasionally published articles on aquaculture.

APPENDIX

Supplementary Films

General oceanography:

Challenge of the Oceans: Oceanography. McGraw-Hill-Text Films. 16 mm., 27 min., sound, color, 1961. BU[1]

Deep Frontier. McGraw-Hill Text-Films. 16 mm., 16 min., sound track on a record, color.

The Earth: Its Oceans. Coronet Films. 16 mm., 14 min., sound, black and white, 1960. BU

History of the U. S. Navy Hydrographic Office. U. S. Navy. 16 mm., 16 min., sound, color. (Order No. FN-8300.)

Mission Oceanography. U. S. Navy. 16 mm., 29 min., sound, color. (Order No. MN-10145.) A 15 minute version (Order No. MN-10145A) is also available.

Science of the Sea. International Film Bureau. 16 mm., 19 min., sound, color, 1958. BU

Biology:

Adaptation to a Marine Environment. McGraw-Hill Text-Films. 16 mm., 19 min., sound, color.

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[1] Films available for rent from the Abraham Krasker Memorial Film Library, Boston University.

Bird Wing Adaptations. International Film Bureau. 16 mm., 17 min., sound, color, 1964. BU

Birds that Eat Fish. International Film Bureau. 16 mm., 6 min., sound, color, 1952. BU

Classifying Plants and Animals. Coronet Films. 16 mm., 11 min., sound, color, 1961. BU

The Colourful Cuttle. International Film Bureau. 16 mm., 14 min., sound, color, 1962. BU

The Crayfish. McGraw-Hill Text-Films. 16 mm., 15 min., sound, color, 1966. BU

Crustaceans: Lobsters, Barnacles, Shrimps and Their Relatives. Encyclopedia Britannica Films. 16 mm., 14 min., sound, color or black and white, 1955. BU

Echinoderms: Sea Stars and Their Relatives. Encyclopedia Britannica Films. 16 mm., 17 min., sound, color, 1962. BU

The First Many-Celled Animals: The Sponges. Encyclopedia Britannica Films. 16 mm., 17 min., sound, color, 1962. BU

The Invertebrates. Coronet Films. 16 mm., 14 min, sound, color, 1962. BU

The Life Cycle. Indiana University. 16 mm., 29 min., sound, black and white, 1958. (Survival in the Sea Series.) BU

Life on the Coral Reef. Indiana University. 16 mm., 29 min., sound, black and white, 1958. (Survival in the Sea Series.) BU

The Marine Biologist. Encyclopedia Britannica Films. 16 mm., 14 min., sound, color, 1963. BU

Marine Ecology. McGraw-Hill Text-Films. 16 mm., 28 min., sound, color.

Marshland Is Not Wasteland. U. S. Department of the Interior, Bureau of Sport Fisheries and Wildlife. 16 mm., 16 min., sound, color, 1963. BU

Mollusks: Snails, Mussels, Oysters, Octopuses and Their Relatives. Encyclopedia Britannica Films. 16 mm., 14 min., sound, color or black and white, 1955. BU

Mysteries of the Deep. Walt Disney Productions. 16 mm., 28 min., sound, color, 1961. (True Life Adventure Nature Series.) BU

Noisy Underwater World of the Weddell Seal. Sterling Educational Films. 16 mm., 11 min., sound, color.

Origin of Life: Chemical Evolution. Encyclopedia Britannica Films. 16 mm., 12 min., sound, color. BU

Photosynthesis. Encyclopedia Britannica Films. 16 mm., 21 min., sound, color, 1963. (The Biology Series. Unit 2, Plant Life.) BU

Plankton: Pastures of the Ocean. Encyclopedia Britannica Films. 16 mm., 10 min., sound, color, 1965. (Basic Life Science Series. Plant and Animal Relationships.) BU

Protozoa: Structures and Life Functions. Coronet Films. 16 mm., 16 min., color, sound, 1965. BU

Seashore Life. Encyclopedia Britannica Films. 16 mm., 11 min., sound, color.

Secrets of the Underwater World. Walt Disney Productions. 16 mm., 16 min., sound, color, 1961. (The Secrets of Life Series.) BU

Sounds in the Sea. Moody Institute of Science. 16 mm., 15 min., sound, color, 1954. BU

Sponges and Coelenterates: Porous and Sac-Like Animals. Coronet Films. 16 mm., 11 min., sound, color, 1962. BU

Strange Partners: Symbiosis in the Sea. Sterling Movies. 16 mm., 16 min., sound, color.

Survival in the Sea: The Life Cycle. Indiana University. 16 mm., 29 min., sound, color or black and white.

Water and Life. Film Associates of California. 16 mm., 15 min., sound, color, 1966. BU

Geology:

The Beach, a River of Sand. Encyclopedia Britannica Films. 16 mm., 20 min., sound, color, 1966. BU

The Land Beneath the Sea. U. S. Navy. 16 mm., 25 min., sound, color, 1967. (Order No. MN-10280.)

Oceanography: Science of the Sea. Film Associates of California. 16 mm., 11 min., sound, color, 1962. BU

Rocks that Form on the Earth's Surface. Encyclopedia Britannica Films. 16 mm., 16 min., sound, color, 1965. BU

Rocks that Reveal the Past. Film Associates of California. 16 mm., 12 min., sound, color, 1962. BU

Understanding Our Earth: Glaciers. Coronet Films. 16 mm., 11 min., sound, color or black and white, 1952. BU

Volcano Surtsey. Capitol Film Laboratories, Inc. 16mm., 30 min., sound, color.

What's Under the Ocean. Film Associates of California. 16 mm., 14 min., sound, color, 1960. BU

The World of Jacques Yves Cousteau. Encyclopedia Britannica Films. 16 mm., 48 min., sound, color, 1967. BU

Man-in-the-sea, submersibles, diving:

The Dolphins that Joined the Navy. U. S. Navy. 16 mm., 27 min., sound, color, 1964. (Order No. MN-10199.)

Flying at the Bottom of the Sea (Submarine Alvin). Indiana University. 16 mm., 30 min., sound, black and white, 1967. BU

Footprints in the Sea. U. S. Navy. 16 mm., 26 min., sound, color, 1966. (Order No. MN-10314.)

Man in the Sea: The Story of Sea Lab II. U. S. Navy. 16 mm., 28 min., sound, color, 1966. (Order No. MN-10110OB.)

Man Invades the Sea. McGraw-Hill Text-Films. 16 mm., 28 min., sound, black and white, 1966. BU

Scientist in the Sea. U. S. Navy. 16 mm., 16 min., sound, color. (Order No. MN-10320.)

Tomorrow's World: Man and the Sea. McGraw-Hill Text-Films. 16 mm., 52 min., sound, color. BU

Meteorology:

The Unchained Goddess. Bell System. 16 mm., 60 min., sound, color. Free on loan.[2]

Weathermen of the Sea. National Audiovisual Center. 16 mm., 14 min., sound, black and white.

Oceanic circulation:

Ocean Currents. McGraw-Hill Text-Films. 16 mm., 17 min., sound, color, 1963. (General Science Film Series.) BU

Water Masses of the Ocean. U. S. Navy. 16 mm., 45 min., sound, color. (Order No. MN-10064.)

Physical and chemical properties of sea water:

The Nature of Sea Water. U. S. Navy. 16 mm., 29 min., sound, color, 1967. (Order No. MN-10317.)

Sea ice:

Time Lapse Study of Antarctic Ice Floes and Tidal Currents. U. S. Navy. 16 mm., 26 min., sound, color. (Order No. MN-10152.)

Tides:

Ocean Tides: Bay of Fundy. Encyclopedia Britannica Films. 16 mm., 14 min., sound, black and white, 1957. BU

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[2] For a listing of other films that are available free of charge see:

Mary Horkheimer Saterstrom, editor. Educators' Guide to Free Science Materials. Randolph, Wisconsin: Educators' Progress Service, Inc. $8.50. Published annually.

Tides of the Ocean: What They Are and How the Sun and Moon Cause Them. Academy Films. 16 mm., 17 min., sound, color, 1964. BU

Miscellaneous:

Frames of Reference. Modern Learning Aids. 16 mm., 30 min., sound, black and white.

Myth, Superstition and Science. International Film Bureau. 16 mm., 13 min., sound, color, 1960. BU

New England Fisherman, 2nd edition. Encyclopedia Britannica Films. 16 mm., 11 min., sound, color. BU

Distributors' Addresses

Abraham Krasker Memorial
Film Library
Boston University, School of
Education
765 Commonwealth Avenue
Boston, Massachusetts 02215

Academy Films
748 North Seward Street
Hollywood, California 90038

Bell System
Films available from your local Bell System representative or affiliated company.

Capitol Film Laboratories, Inc.
1905 Fairview Avenue, N. E.
Washington, D. C. 20002

Committee on Oceanography
National Academy of Sciences-
National Research Council
2101 Constitution Avenue, N. W.
Washington, D. C. 20418
Address inquiries to
Mr. Richard C. Vetter

Coronet Films
65 E. South Water Street
Chicago, Illinois 60601

Encyclopedia Britannica Films
1150 Wilmette Avenue
Wilmette, Illinois 60091

Indiana University
Audio-Visual Center
Bloomington, Indiana 47405

International Film Bureau
332 S, Michigan Avenue
Chicago, Illinois 60604

Film Associates of California
11014 Santa Monica Boulevard
Lost Angeles, California 90025

McGraw-Hill Text-Films
330 West 42nd Street
New York, New York 10018

Modern Learning Aids
16 Spear Street
San Francisco, California 94105

Moody Institute of Science
Education Film Division
12000 E. Washington Boulevard
Whittier, California 90606

National Audiovisual Center (GSA)
Sales Branch
Washington, D. C. 20409

Sterling Educational Films
241 East 34th Street
New York, New York 10016

Sterling Movies
309 W. Jackson Boulevard
Chicago, Illinois 60606

U. S. Department of the Interior
Bureau of Sport Fisheries
and Wildlife
Films available from your local
Regional Office.

U. S. Navy
Films available from the
Assistant for Public Affairs of
your Naval District, or from the
National Audiovisual Center.

Walt Disney Productions
477 Madison Avenue
New York, New York 10022